DEVELOPMENT OF CONVENTIONAL AND FUZZY CONTROLLERS FOR OUTPUT COUPLED DRIVE SYSTEMS AND VARIABLE INERTIA

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Abstract: The control of output coupled drive systems having variable inertia is difficult due to the presence of possible vibrations due to the elastic coupling, the variance of plant parameters, and the effect of output coupling of the control sub-systems. Typical applications for such complex large-scale multivariable systems are the fields of rolling mills, of winding mechanisms, and of electrical driven transportation systems. The paper presents results concerning the development of conventional and fuzzy control solutions for a drive system with two output coupled motors applicable to the rolls of a hot rolling mill and to a variable inertia strip winding system.

Keywords: Conventional control, fuzzy control, angular velocity, cascade control, state feedback, sliding-mode control.

1. INTRODUCTION

The control of output coupled drive systems with variable inertia represents a difficult but challenging task due to the following reasons: the effect of output coupling of control sub-systems, the presence of possible vibrations due to the elastic coupling, the variance of plant parameters.

Typical applications for such systems are found in the field of rolling mills and of winding mechanisms. These systems represent large-scale multivariable plants for which several control solutions can be given including the conventional and fuzzy ones.

The paper presents some research results in controllers development for a drive system with two output coupled motors applicable to the rolls of a hot rolling mill and to a variable inertia strip winding system.

2. DIAGRAMS OF PRINCIPLE, MATHEMATICAL MODELS AND BLOCK DIAGRAMS

2.1 Milling Process. Principles

The diagram of principle for rolling a strip is presented in Fig.1, where the strip can pass through several stands, and only one stand is highlighted.

The characteristic variables representing the basis for the mathematical modeling of the plant are (Ginzburg, 1989): v_i, v_o – the strip linear velocity; h_i, h_o – the strip thickness; σ_i, σ_o – strip tension; R – the work roll radius; i, o – indices standing for the input (entry) and output (exit), respectively.

The exit thickness h_o depends on the distance between the rolls (the position of the capsule) d and on the rolling force F:

$$h_o = d + k \cdot F , \quad (1)$$

with k – constant characterizing the mill material (inverse of the mill modulus). The strip exit velocity v_o depends on R, on the slip s which occurs between the strip and the work roll surface and on the stand motor angular speed ω:

$$v_o = (1 + s) \cdot R \cdot \omega , \quad (2)$$

The mass-flow conservation equation complements the equations (1) and (2):

$$h_i v_i = h_o v_o \quad \text{or} \quad v_o = v_i h_i / h_o . \quad (3)$$

The entire milling process depends on the material temperature, θ_i and θ_o. The strip tension σ(t) can be characterized by the equation (4):

$$\sigma(t) \approx E\, \Delta l_b(t)/L_0 , \quad (4)$$

where E represents Young's modulus of elasticity, $\Delta l_b(t)$ is the strip longitudinal strain, and L_0 stands for the distance between two successive stands.

In order to ensure the exit strip thickness there is necessary a series of successive stands with their characteristic variables ω and F to be controlled. The stability of the rolling process is determined by the existence of a looper between any two successive stands, Fig.2. The looper position, defined by the angle α, determines the strip tension σ.

The drive motors angular speeds of the successive stands must be correlated with (2) and (3). Consequently, the control problems at the level of two successive stands involve:

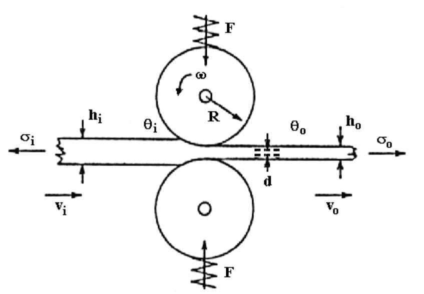

Fig.1. Characteristic variables of strip rolling plant.

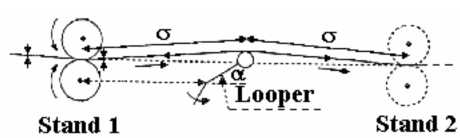

Fig.2. Position of looper system.

- to ensure the rolling forces for maintaining the desired value of the distance between rolls (d);
- to ensure a well stated looper position (α), that determines the strip thickness;
- to stabilize and synchronize the stand motors angular speeds (ω_{vi}) and the drive motors angular speeds (ω_{mi}).

2.2 *Electrical Drive System of Two Successive Rolls of a Strip Rolling Mill (RDS)*

In a version derived from Fig.2, this system (briefly, Rolls Drive System, RDS), has the diagram of principle presented in Fig.3 (Preitl, *et al.*, 1998), (Porumb, 1997). The diagram contains two DC motors, M1 and M2, coupled to the rolls by means of a shaft having the ratio length/diameter of approximately 20, which determines the existence of RDS elasticity.

The drive motors M1 and M2 are just "almost identical" which requires their separate mathematical modeling. The primary equations describing the system operation can be expressed as:

$$\begin{aligned}
&k_{ch1}u_{c1}(t)=L_{a1}i_{a1}'(t)+R_{a1}i_{a1}(t)+k_{e1}\omega_{m1}(t) ,\\
&k_{ch2}u_{c2}(t)=L_{a2}i_{a2}'(t)+R_{a2}i_{a2}(t)+k_{e2}\omega_{m2}(t) ,\\
&J_{m1}\omega_{m1}'(t)=k_{m1}i_{a1}(t)-m_{c1}(t) ,\\
&J_{m2}\omega_{m2}'(t)=k_{m2}i_{a2}(t)-m_{c2}(t) ,\\
&m_{c1}(t)=d_1[\omega_{m1}(t)-\omega_{v1}(t)]+c_1\Delta\theta_1(t) , \qquad (5)\\
&m_{c2}(t)=d_2[\omega_{m2}(t)-\omega_{v2}(t)]+c_2\Delta\theta_2(t) ,\\
&J_{v1}\omega_{v1}'(t)=m_{c1}(t)-r_{v1}F_{12}(t)-k_{fs1}\omega_{v1}(t) ,\\
&J_{v2}\omega_{v2}'(t)=m_{c2}(t)-r_{v2}F_{12}(t)-k_{fs2}\omega_{v2}(t) ,\\
&\Delta l_b'(t)=(1/r_{v2})\omega_{v2}(t)-(1/r_{v1})\omega_{v1}(t) ,\\
&F_{12}(t)=c_b\Delta l_b(t)+F_{01}(t) ,
\end{aligned}$$

where the upper index " ' " stands for the derivative of a certain variable with respect to time (t), and the variables and parameters have the significance well acknowledged in literature (Tramaseur, 1967).

The state variables characterizing the RDS are: $\{x_1=i_{a1},\ x_2=i_{a2},\ x_3=\omega_{m1},\ x_4=\omega_{m2},\ x_5=\omega_{v1},\ x_6=\omega_{v2},\ x_7=\Delta\theta_1,\ x_8=\Delta\theta_2,\ x_9=\Delta l_b\}$.

By rearranging the primary equations and neglecting the backlash (in the reduction gear box) and dry friction there is obtained a linear state-space mathematical model and, based on this, there can be built the informational block diagram of the system, illustrated in Fig.4.

From the point of view of controlling the RDS there are of interest the absorbed currents i_{a1} and i_{a2}, the drive motors angular speeds ω_{m1} and ω_{m2} (these variables are accessible to measurements), the stand motors angular speeds ω_{v1} and ω_{v2}, and the strip longitudinal stress force F_{12}. The control goal is to keep constant the angular speeds ω_{v1} and ω_{v2} and the strip longitudinal stress force F_{12}.

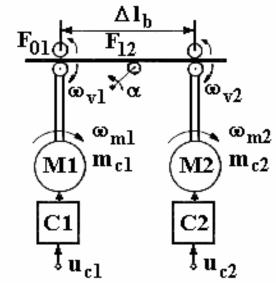

Fig.3. Functional diagram of Rolls Drive System.

The controllers development in order to fulfil the above mentioned goal is based on the transfer functions expressed in Table 1, where the abbreviation $H_{xy}(s)=x(s)/y(s)$ is used. These transfer functions point out the major difficulties to appear when this system is stabilized.

The two polynomials appearing in Table 1, $\Delta_1(s)$ and $\Delta_2(s)$, can be expressed in terms of (6):

$$\begin{aligned}\Delta_1(s)=&[(J_{m2}J_{v2})/(c_bc_2)]s^4+[(d_2J_{m2}+d_2J_{v2}+k_{fs2}J_{m2})/\\ &/(c_bc_2)]s^3+[(c_2J_{m2}+c_2J_{v2}+c_bJ_{m2}+k_{fs2}d_2)/(c_bc_2)]s^2+\\ &+[(c_bd_2+c_2k_{fs2})/(c_bc_2)]s+1\}\ , \qquad (6)\\ \Delta_2(s)=&[(J_{m1}J_{v1})/(c_bc_1)]s^4+[(d_1J_{m1}+d_1J_{v1}+k_{fs1}J_{m1})/\\ &/(c_bc_1)]s^3+[(c_1J_{m1}+c_1J_{v1}-c_bJ_{m2}+k_{fs2}d_1)/(c_bc_1)]s^2+\\ &+[(-c_bd_1+c_1k_{fs1})/(c_bc_1)]s+1\}\ .\end{aligned}$$

2.3 Variable Inertia Drive System (VIDS)

Usually at the exit the strip is winded on a drum rolling with a velocity which should be synchronized with the strip linear velocity. The functional diagram of the drive system is presented in Fig.5.

The state-space mathematical model of VIDS (Solyom, 1999), (Kovacs, 2000) has the state variables $\{x_1=i_a,\ x_2=\omega_m,\ x_3=f_t\}$:

$$\begin{aligned}x_1'(t)=&-(R_a/L_a)x_1(t)-(k_e/L_a)x_2(t)+(k_{ch}/L_a)u_c(t)\ ,\\ x_2'(t)=&(k_m/J_e(t))x_1(t)-(1/J_e(t))(J_e'(t))x_2(t)-\\ &-(r_t(t)/J_e(t))x_3(t)-(1/J_e(t))m_f(x_2(t))\ , \qquad (7)\\ x_3'(t)=&c_br_t(t)-c_bv_s(t)\ .\end{aligned}$$

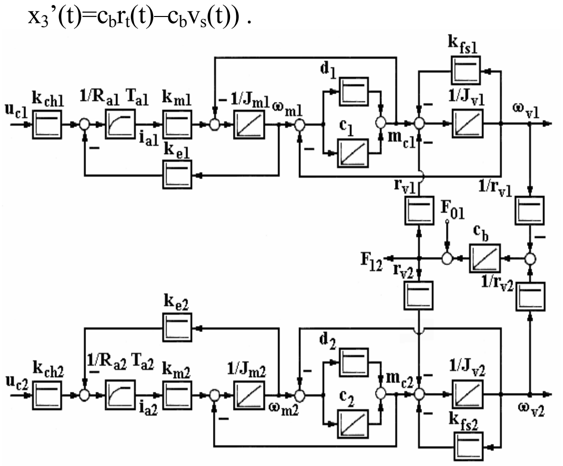

Fig.4. Informational block diagram of RDS.

Table 1 Transfer functions of RDS

Transfer function	Expression B(s)/A(s)
$H_{\omega v1\omega m1}(s)$	$B(s)=(d_1/c_1)s+1$, $A(s)=(J_{m1}/c_1)s^2+(d_1/c_1)s+1$
$H_{\omega v2\omega m2}(s)$	$B(s)=(d_2/c_2)s+1]$, $A(s)=(J_{m2}/c_2)s^2+(d_2/c_2)s+1$,
$H_{F12\omega m1}(s)$	$B(s)=-(r_{v1}/k_{fs1})[(d_1/c_1)s+1]$, $A(s)=[(J_{m1}J_{v1})/(c_1k_{fs1})]s^3+[(d_1J_{m1}+ +d_1J_{v1}++k_{fs1}J_{m1})/(c_1k_{fs1})]s^2+[(c_1J_{m1}++ c_1J_{v1}+k_{fs1}d_1)/(c_1k_{fs1})]s+1$
$H_{F12\omega m2}(s)$	$B(s)=-(r_{v2}/k_{fs2})[(d_2/c_2)s+1]$, $A(s)=[(J_{m2}J_{v2})/(c_2/k_{fs2})]s^3+[(d_2J_{m1}+ +d_2J_{v2}+k_{fs2}J_{m2})/(c_2k_{fs2})]s^2+[(c_2J_{m2}+ +c_2J_{v2}+k_{fs2}d_2)/(c_2k_{fs2})]s+1$
$H_{\omega v2\omega v1}(s)$	$B(s)=-(r_{v2}/r_{v1})[(J_{m2}/c_2)s^2+ +(d_2/c_2)s+1]$, $A(s)=\Delta_1(s)$
$H_{\omega v1\omega v2}(s)$	$B(s)=-(r_{v1}/r_{v2})[(J_{m1}/c_1)s^2+ +(d_1/c_1)s+1]$, $A(s)=\Delta_2(s)$

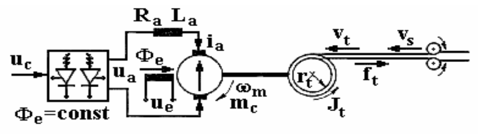

Fig.5. Functional diagram of VIDS.

The model (7) is strongly nonlinear as it results from the block diagram presented in Fig.6:

3. SPEED CONTROL SOLUTIONS

The solution with conventional control lops with interactions deals with controlling:
- the distance d between the rolls by means of the rolling force;
- the looper angle α;
- the angular speeds of coupled successive stands.

Some control aspects concerning these structures are presented in (Grimble and Hearns, 1999). The authors have analyzed and presented in detail in (Preitl, *et al.*, 1998), (Solyom, 1999), (Kovacs, 2000) some conventional as well as fuzzy control solutions concerning to the control structures of interest.

The particular difficulties appearing in the design and implementation of such structures are:
- the existence of coupling by the common output of the subordinated systems requesting the achievement of systems with reference input compensation;
- the presence of elasticity of shaft, the backlash and the stick-slip;
- the modification of the inertia moment during the operation of the plant.

These particular features require the opportunity of:

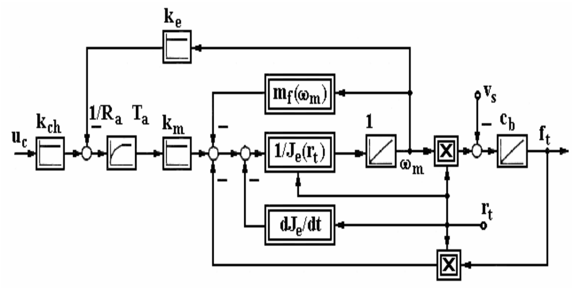

Fig.6. Informational block diagram of VIDS.

- using non-conventional control structures;
- framing the local control solutions into multivariable, integrated structures.

3.1 Conventional Structures

The basic conventional control structure of a RDS is the cascade control one, Fig.7, with the feedback with respect to the speed, in two possible versions.

Depending on the position of the stand (i), the speed reference input $\omega_{o(i)}$ is generated as function of the deviation of roller angle $\alpha_{(i)}$ from the imposed value α_o, and of the ratio of angular velocities $\omega_{(i)}/\omega_{(i+1)}$ for two successive stands, determined by the mass-flow compensation (see (2) and (3)).

For the two controllers, C-i and C-ω, there were successively chosen the following two versions.

First version of conventional control structure. C-i and C-ω are of conventional PI-type with Anti-Reset-Windup (ARW) measure for the speed control loop. The two controllers were designed by the Modulus Optimum Method (for C-i) (Åström and Hägglund, 1995), and by the Extended Symmetrical Optimum Method in two versions (ESO and MS-ESO) (for C-ω) (Preitl and Precup, 1999, 2000). For the alleviation of oscillations due to the elasticity there was tested the solution of a disturbance estimator with derivative character, Fig.8. The solution was tested by digital simulation for a case study.

Second version of conventional control structure. C-i is a conventional controller, and C-ω is a fuzzy one, with a classical structure (Precup and Preitl, 1999). The advantage of this solution can be justified by the modification of controller behavior in two specific regimes: no load starting up and milling. The solution was tested also by digital simulation for a case study (Preitl, *et al.*, 1999a).

3.2 State Feedback Structure

For the control of any control loop there was selected the structure with control error compensation (CECB – control error correction block) according to Fig.9.

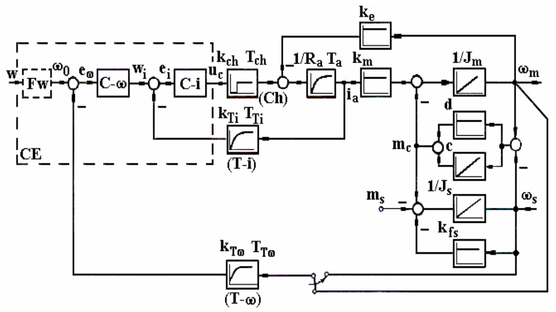

Fig.7. Cascade control structure.

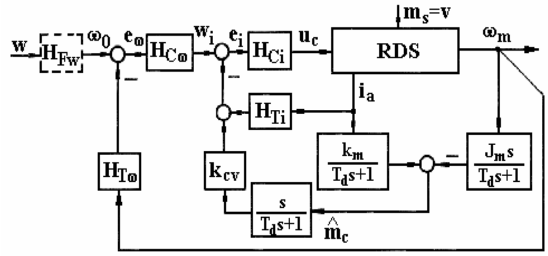

Fig.8. Extended cascade control structure.

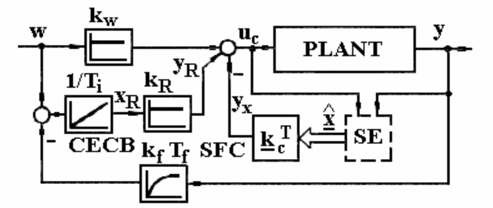

Fig.9. Basic state feedback control structure with control error compensation.

Each local structure has the reference input corrected in terms of those presented in Section 3.1. The state variables of each sub-plant are the armature current, the motor speed, the roll angular speed, and the difference $\Delta\theta$ between the positions of the two axes. There was also tested the situation of using some state observers of complete or reduced order.

The state feedback control structures and the corresponding observers were designed by pole placement on an ellipse (Preitl and Porumb, 1994), (Porumb and Preitl, 1996).

3.3 Sliding Mode Control Structure

There was considered a state feedback sliding mode control structure without (Fig.10) or with state estimator (SE), with reference input compensation as in Section 3.1 (SB – switching block).

4. WINDING SYSTEM CONTROL SOLUTIONS

The winding process has variable inertia, and the reference input must be correlated with the modification of work roll radius.

In this context two basic aspects occur at the development of the control structure: the modification of the reference input (ω), and the tuning of controller parameters. For the first one there was tested the solution based on:

$$v(t) = \text{const} \;\; \rightarrow \;\; \omega_o(t) = k/R(t) \, , \qquad (8)$$

where by the measurement of R(t) there can be ensured the continuous modification of the reference input $\omega_o(t)$. The extension of the reference block with a correction module to take into account the strip tension is advantageous (Fig.11).

The problem of controlling the speed of the winding system can be solved in two ways: by the use of a cascade control structure with two, current and speed, controllers, or by the use of a state feedback control structure. For both versions, the variance of the moment of inertia, according to (9):

$$J(t) = (1/2) \bullet \rho \bullet \pi \bullet l \bullet R^4(t) \, , \qquad (9)$$

requires much attention in the controller design. In this context, there were analyzed and tested several control solutions such as (Preitl, *et al.*, 1999b): solutions with error based control loops with linear PI (to be presented in Section 4.1) and PI-fuzzy controllers with parameter adaptation (to be presented in Section 4.3), conventional (to be presented in Section 4.2) and fuzzy state feedback control solutions with parameter adaptation (to be presented in Section 4.4).

4.1 Cascade Control Structure

The speed controller design is based on the ESO Method applied in two versions (Preitl and Precup, 1999), (Porumb, *et al.*, 1997): constant parameters tuned for the medium value of the moment of inertia with maximum phase reserve, and parameters tuned for a maximum phase reserve and re-tuned as function of radius modification. The second version permits the obtaining of better control system performance.

4.2 Adaptive State Feedback Control Structure

The diagram of principle of this solution is presented in Fig.12 (with the state variables $\{i_a, \omega\}$).

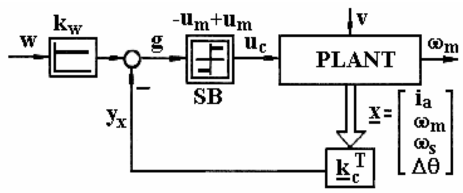

Fig.10. State feedback sliding mode control structure.

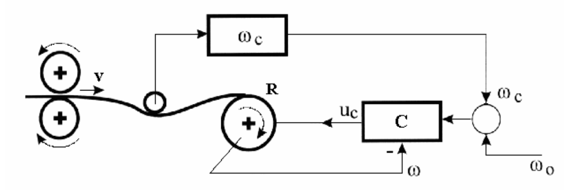

Fig.11. Reference input correction system.

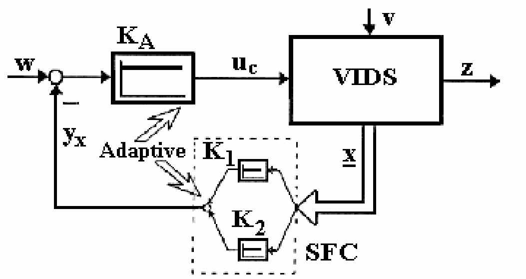

Fig.12. Adaptive state feedback control structure.

For the development of the strategy for adaptation of the parameters K_A, K_1 and K_2 there was started from a mathematical model, linearized in the vicinity of a state trajectory, of the form (Solyom, 1999):

$$x_1'(t) = -(R_a/L)x_1(t) - (K_e/L)x_2(t) + (K_{EE}/L)u_1(t) \, ,$$
$$x_2'(t) = [K_M/J(t)] - \alpha(t)x_2(t) - a[r(t)/J(t)]u_2(t) \, , \text{ with}$$
$$\alpha(t) = 2\rho a^5 \, l \, h[r^3(t)\omega(t)/J(t)] + K_{CE}/J(t) \, . \qquad (10)$$

where $\{R_a, L, K_e, K_{EE}, K_M, J(t), K_{CE}, \rho, a, l, h, r(t)\}$ are parameters characterizing the plant, and ω(t) stands for the linearization trajectory. The parameters of the state feedback compensator (SFC) depend on the position of closed-loop system poles $\{p_1, p_2\}$ according to:

$$K_1(t) = -(1/K_A/K_{EE})[L(p_1+p_2+\alpha(t))+R_a] \, ,$$
$$K_2(t) = [LJ(t)/K_M/K_A/K_{EE}][\alpha^2(t)+(p_1+p_2)\alpha(t)+$$
$$+p_1p_2-K_MK_e/L/J(t)] \, , \text{ with}$$
$$K_A(t) = [R_ax_1(t)+K_ex_2(t)]/K_{EE}/[w-$$
$$-K_1(t)x_1(t)-K_2(t)x_2(t)] \, . \qquad (11)$$

The solution was tested by simulation in (Solyom, 1998).

For an as correct as possible pole placement it is useful to perform the analysis of the sensitivity of the SFC block with respect to the modification of radius. There are defined and computed the following sensitivity functions:

$$S_r^{K1} = -(L/K_A/K_{EE})[\partial\alpha(r)/\partial r] \, , \qquad (12)$$

$$S_r^{K2} = [L\alpha^2(r)+L(p_1+p_2)\alpha(r)+Lp_1p_2-$$
$$-K_MK_e/J(r)][\partial J(r)/\partial r]+\{2L\alpha(r)[\partial\alpha(r)/\partial r]+$$
$$+L(p_1+p_2)[\partial\alpha(r)/\partial r]+$$
$$+K_MK_e/J^2(r)[\partial J(r)/\partial r]\}J(r)/K_M/K_A/K_{EE} \, , \qquad (13)$$

where the parameter α(r) characterizes the quantity of strip winded on the roll. The analysis of the two sensitivity functions versus time for a case study on a finite time interval points out the decrease of K_1 sensitivity and the increase of K_2 sensitivity (Solyom, 1999).

4.3 Quasi-PI Fuzzy Controllers

In the evolution of their development, there are of interest in the context of the speed control loop three fuzzy controllers (FCs) analyzed in (Precup and Preitl, 1997a): the standard quasi-PI fuzzy controller (PI-FC), the predictive FCs, and the adaptive FCs.

The standard PI-FC is based on one of the structures from Fig.13, having as characteristic feature: for the standard PI-FC with integration on controller output (PI-FC-OI, Fig.13-a) the dynamics is introduced by differentiating the control error (e_k) and integrating the increment of control signal (Δu_k), and for the standard PI-FC with integration on controller input (PI-FC-II, Fig.13-b) the dynamics is introduced by integrating e_k.

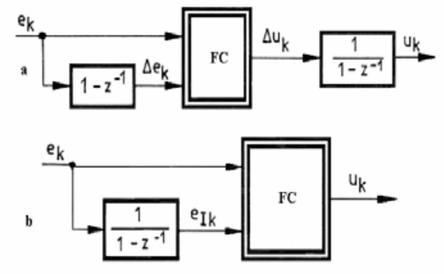

Fig.13. Structures of standard PI-FCs.

The membership functions for both fuzzy controllers are of the type presented in Fig.14, and the decision table is shown in Table 2.

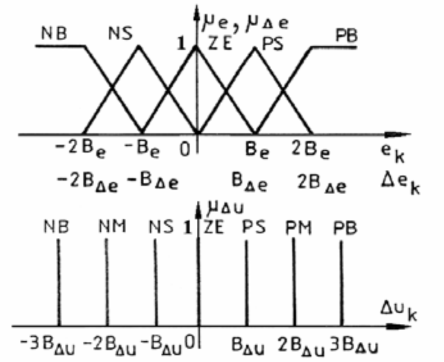

Fig.14. Membership functions of PI-FC-OI.

Table 2 Decision table of PI-FC-OI

$\Delta e_k \backslash e_k$	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 parameters of these PI-FCs are $\{B_e, B_{\Delta e}, B_{\Delta u}\}$ for the standard PI-FC-OI, and $\{B_e, B_{eI}, B_u\}$ for the standard PI-FC-II.

The predictive fuzzy controllers (PFCs) are based on the incremental version of the digital PID controller (IDPIDC) (Tzafestas, 1985):

$$\Delta u_k = K_P e_k + K_P \Delta e_k + K_D \Delta^2 e_k \,, \qquad (14)$$

where: u_k – the control signal; $\Delta e_k = e_k - e_{k-1}$ – the first increment of control error; $\Delta^2 e_k = \Delta e_k - \Delta e_{k-1} = e_k - 2e_{k-1} + e_{k-2}$ – the second increment of control error; $\{K_P, K_I, K_D\}$ – the parameters of the IDPIDC.

In (Precup and Preitl, 1995) there were presented two versions of digital PID predictive controllers (DPIDPCs):
- the DPIDPC with first order prediction (DPIDPC-P1) based on predicting the control error in terms of (15):

$$e_k = 2\, e_{k-1} - e_{k-2} \,, \qquad (15)$$

and on the substitution of it in (14). The following discrete equation is obtained:

$$\Delta u_k = K_{PI}\,(\Delta e_{k-1} + \beta\, e_{k-1}) \,, \qquad (16)$$

with K_{PI} and β being expressed according to (Precup and Preitl, 1995);
- the DPIDPC with second order prediction (DPIDPC-P2) based on (17) (Tzafestas, 1985):

$$e_k = 2.5\, e_{k-1} - 2\, e_{k-2} + 0.5\, e_{k-3} \,. \qquad (17)$$

The substitution of e_k from (17) in (14) yields:

$$\Delta u_k = 0.5 K_{PID} \Delta^2 e_{k-1} + K_{PI}(\Delta e_{k-1} + \beta e_{k-1}) \,, \qquad (18)$$

where the parameter K_{PID} has the expression from (Precup and Preitl, 1995).

The considered versions of predictive PFCs are the followings.

First order PFC. It has the characteristic feature in the fact that the equation (16) for the DPIDPC-P1 is similar to the discrete equation of an incremental digital PI controller (IDPIC); therefore, a FC approximately equivalent to the controller (16) can be derived as in the case of the PI-FC-OI; the proposed fuzzy controller has: two inputs (e_{k-1} and Δe_{k-1}) and one output (Δu_k), the membership functions from Fig.14 and the decision table from Table 2; it is based on Mamdani's max-min compositional rule of inference and on the center of gravity method of defuzzification.

Second order PFCs. They have the characteristic feature in the fact that the crisp equation (18) for the DPIDPC-P2 can be transposed in a fuzzy expression by two ways (Precup and Preitl, 1995) resulting in two versions of PFCs: for the first one, Δu_k is obtained by the addition of the crisp term $\Delta u_k^c = 0.5\ K_{PID}\Delta^2 e_{k-1}$ to the increment of control signal Δu_k^I given by the PFC presented above, and for the second one, The term Δu_k^c can be provided by another FC resulting in a parallel connection of two FCs.

The digital simulation results confirmed the viability of the proposed PFCs.

The research results reported in (Precup and Preitl, 1997a) highlight the development of five versions of adaptive fuzzy controllers (AFCs): the FC with fuzzy tuning of the parameters of an IDPIC as function of e_k and Δe_k; the FCs with fuzzy tuning of membership function shapes of the input and output linguistic terms of a standard PI-FC-OI and of a standard PI-FC-II as function of e_k; the FCs with fuzzy tuning of the gain of a standard PI-FC-OI and of a standard PI-FC-II as function of e_k.

The comparative analysis of the solutions of fuzzy controllers on a simulated case study pointed out the following aspects: the PFCs and the AFCs provide better control system performance in comparison with conventional controllers when they cope with plants with integrating behavior. The best behavior with respect to the modification of reference input is provided by the first AFC; the best behavior with respect to the modification of disturbance input is provided by the fourth AFC; the best behavior with respect to parameter variations is provided by the second AFC; due to the presence of the I component in controller structure, all FCs lead to control systems with zero zero steady-state control error.

4.4 State Feedback Fuzzy Controllers

The use of these controllers can be justified by the presence of nonlinearities and by the variance of the parameter J(t). There are presented in this Section two state feedback control solutions with components of fuzzy processing of information, analyzed by the authors.

The sliding mode control solution with fuzzy logic blocks. The solution was adapted to a state feedback sliding mode control solution having the structure from Fig.10 (with additional CECB according to Fig.9). A possible solution for control system performance enhancement is in the fuzzification of the conventional controllers CECB and SB. These blocks will be transformed into the fuzzified ones, F-CECB and F-SB, respectively, as it is illustrated in Fig.15 (Precup and Preitl, 1997b), where FB and FAB stand for fuzzy block and fuzzy adaptation block, respectively.

Precup and Preitl (1997b) have presented the development of the state feedback sliding mode controller and of the FB and FAB. Digital simulation were reported for a VIDS.

The state feedback fuzzy controller (SFFC) has the structure presented in Fig.16.

For the systematic development of such a controller the following steps have to be proceeded (Solyom, 1999): the winding system is identified according to a known procedure, than the SFFC is designed. In the final development step, the state feedback fuzzy control system is included in a conventional control loop with PI controller with variable reference input $\omega_0(t)$ depending on the modification of radius.

By taking into account the specific features of the controlled plant, in the step of identification of fuzzy models for it, as part of the possible solutions (Gupta, *et al.*, 1986), there was selected the solutions for the specification of the fuzzy variables of the premise and of the conclusion by associating then the data to these variables.

The developed SFFC was presented by the authors in (Preitl, *et al.*, 1999a, 1999b). The procedure, having general validity, was tested by digital simulation for the VIDS.

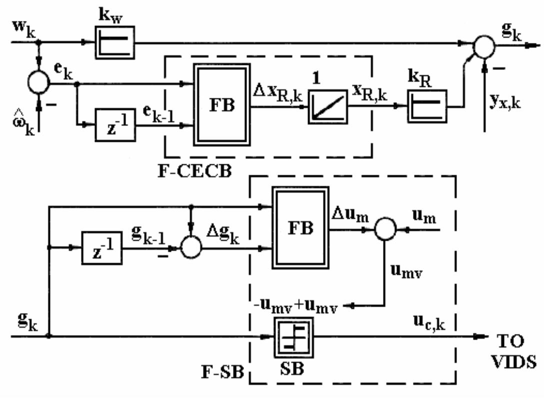

Fig.15. Fuzzification of conventional CECB and SB.

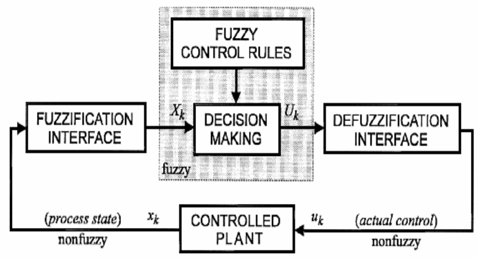

Fig.16. State feedback fuzzy control system.

5. CONCLUSIONS

The paper presents results in the development of conventional and fuzzy control solutions meant for the output coupled drive systems and with variable inertia. There were presented several controllers design techniques, applicable in structures of complex large-scale multivariable systems including rolling mills, winding mechanisms and transportation systems (this is the situation of railway engines).

The presentation was done around a case study corresponding to a drive system with two output coupled motors which can be applied to the rolls of a hot rolling mill and to a variable inertia strip winding system.

There is shown the potential of advanced fuzzy control when it copes with controlling the mentioned class of systems.

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