Control of Electrical Drives Based on Fuzzy Logic

CONSTANTIN VOLOSENCU
Department of Automatics and Applied Informatics
"Politehnica" University of Timisoara
Bd. V. Parvan nr. 2 Timisoara 300223
ROMANIA
constantin.volosencu@aut.upt.ro http://www.aut.upt.ro/~cvolos/

Abstract: - The paper presents the theory of control systems for electrical drives based on fuzzy logic, from the author's point of view. The paper offers practical answers at questions related to the design of speed control systems based on fuzzy PI speed controller: what is the adequate structure of fuzzy controller, the number of rules fuzzy values, how to assure stability, implementation, control system quality criteria. The conventional design method for the linear speed control systems is presented as a comparison base. An example of fuzzy control systems for d.c. drives is given, with its modelling, simulation, design, transient characteristics and quality criteria.

Key-Words: - control systems, fuzzy logic, electrical drives, stability analysis.

1 Introduction

Control technology of electrical drives had a dynamic evolution in the last decades, based on development in power electronics [1], semiconductor devices, power converters [2], PWM methods [3], modelling and simulation [4], electrical machines [5] and drives [6, 7], advanced control techniques based on AC motors [8, 9] and digital signal processors on ASIC technology [10]. The domain is a complex one, for development of modern motion control systems research teams formed with researchers from different multi-disciplinary domains: electrical, electronics, computers, control systems, mechanics are necessary [11]. Motion control systems have applications in industry and at home. The role of motion control systems will increase in the future.

The control of electrical drives provides strong incentives to control engineering in general, leading to the development of new control structures and their introduction to the other area of control [9]. Fuzzy logic [12, 13, 14, 15] is an important tool of artificial intelligence, which used in motion control [16, 17, 18, 19, 20, 21, 22], brings important advantages [23] and increases control quality. The graded membership functions, acquiring the faculty of cognition and perception, make our knowledge base and information processing more efficient. The notion of graded membership adapted in the calculus of fuzzy logic provides more robust algorithms for intelligent systems. Fuzzy PI controllers [24], based on fuzzy sets [25] and defuzzyfication [26] were developed and used in speed control.

Stability is an important property of fuzzy control systems. It is analyzed in the fame of nonlinear systems [27] using many techniques [28, 29, 30, 31, 32, 33].

The author emphasized some algebraic properties of fuzzy controllers [34], developed some ways to implement fuzzy controllers [35], discovered a new method to assure stability of some fuzzy controllers [36, 37], he demonstrated the robustness of fuzzy speed control systems at parameter identification errors [38] and developed fuzzy control systems for the main electric DC and AC drives [39, 40, 41, 42].

In this paper a short survey of the way to develop fuzzy control system for electric drives is presented. The second chapter presents a short survey of the basic principles how to develop a speed control system for a DC drive based on linear PI controller, designed using the phase reserve method, empirical quality criteria, a Simulink model for simulations and some transient characteristics. The third chapter presents the principles how to develop a speed control system based on fuzzy PI controller: the structure of a fuzzy PI speed controller, fuzzyfication, rule base, inference method, defuzzification method, universes of discourse, stability analysis, transient characteristics. A comparison of the quality criteria for the two control systems. Based on this comparison the advantages of fuzzy control are emphasized. An implementation using DSP and fuzzy memory is recommended.

2 Conventional Control Systems

The following paragraphs will present the principles of the speed control systems based on linear PI speed controllers: control structures, block diagrams, controller design methodology, modeling and simulation diagrams, transient regime characteristics.

2.1 Speed Control System for DC Drives

In Fig. 1 a block diagram of a speed control of a DC drive is presented.

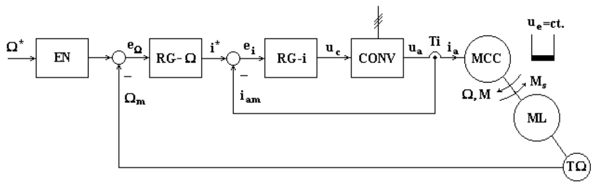


Fig. 1 The structure of a speed control system for a DC drive

The speed control structure from Fig. 1 has the following components: MCC - DC motor, ML - load machine, CONV – power converter, RG-i – current controller, RG-Ω - speed controller, EN – smoothing element, Ti – current sensor, TΩ - speed sensor. The control system variables are: Ω* - speed reference, Ω - motor speed, Ω_m – measured speed, M – motor torque, M_s – load torque, e_Ω - speed error, i* - current reference, i_{am} – measured current, e_i – current error, u_i – command voltage, u_a – motor armature voltage, i_a – current motor, u_e – excitation voltage.

The control system from Fig. 1 has the block diagram from Fig. 2.

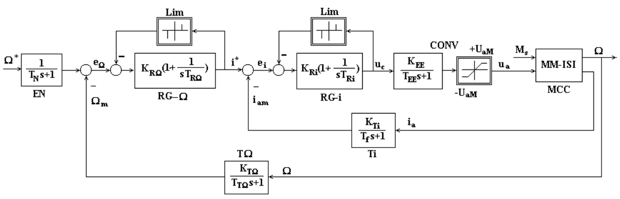


Fig. 2 The block diagram of speed control system of DC drive

The blocks of the control structure from Fig. 1 have the mathematical models from the blocks from Fig. 2. The control system has nonlinear limitation at the speed and current controller (anti-wind-up circuits) and saturation at the converter. The state space equations (MM-ISI) of the DC motor are:

$$\begin{aligned} \frac{di_a}{dt} &= -\frac{R_a}{L_a} i_a - \frac{k_e}{L_a}\Omega + \frac{1}{L_a} u_a \\ \frac{d\Omega}{dt} &= \frac{k_m}{J} i_a - \frac{k_f}{J}\Omega - \frac{1}{J} M_s \\ e &= k_e \Omega \\ M &= k_m i \end{aligned} \tag{1}$$

where R_a and L_a are the armature resistance and inductance, k_e=k_m are the voltage and torque coefficients, J is the inertial moment, k_f is the friction coefficient.

The chosen motor technical characteristics are: P_n=1 kW, U_n=220 V, n_n=3000 rot./min., η=0,75, p=2, J=0,006 kgm^2, M_n=P_n/Ω_n=3,2 Nm, Ω_n=2πn_n/60=314 rad/s, I_n=P_n/η/U_n=6 A, I_M=I_{lim}=1,8I_n=10,8 A, R_a=0,055U_n/I_n=2,01 Ω, L_a=5,6U_n/n_n/p/I_n=0,034 H, T_a=L_a/R_a=0,017 ms, k_e=(U_n–$I_n R_a$)/Ω_n=0,664 Vs, k_m=0,664 Nm/A, k_f=0,08M_n/Ω_n=8.10^{-4} Nms. The speed sensor has the following parameters: $K_{T\Omega}$=0,1/π Vs, $T_{T\Omega}$= 10ms. The converter has the following parameters: K_{EE}=22, T_{EE}=2 ms, U_{aM}=240 V. The current sensor has the following parameters: T_f=5 ms. K_{Ti} = 1 V/A.

2.2 Control System Design

The current controller is designed using the frequency characteristics of the current open loop [9], imposing a phase reserve around of 35^o, or the module criterion in Kessler's variant for a 4,3 % current overshoot. The current open loop frequency characteristics are presented in Fig. 3.

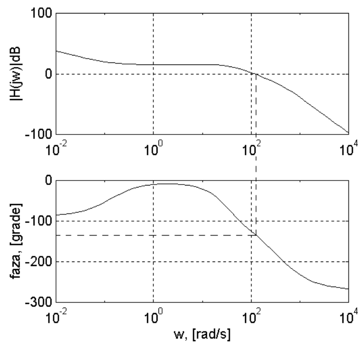


Fig. 3 Frequency characteristic of current open loop

The current controller has the following parameters: K_{RGi}=0,2, T_{RGi}=T_a=L_a/R_a=0,017 s.

The speed controller is designed using the frequency characteristics of the speed open loop [9], imposing a phase reserve around 55°, or the symmetry criterion in Kessler's variant for a 43 % speed overshoot. The speed open loop frequency characteristics are presented in Fig. 4.

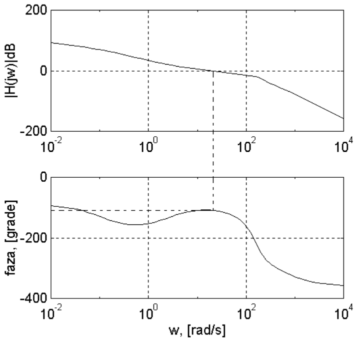


Fig. 4 Frequency characteristic of the speed open loop

The speed controller has the following parameters: $K_{RG\Omega}$=0,8, $T_{RG\Omega}$=0,4 s.

For the time constant of the EN element the value of T_N=4T_a=0,068 s was chosen. With this value a speed overshoot of 7,4 % is obtained.

2.3 Modeling and Simulation

A Simulink model, presented in Fig. 5, was developed for modeling and simulation of the speed control system from Fig. 1 and 2 and for obtaining the frequency characteristics of the open loops.

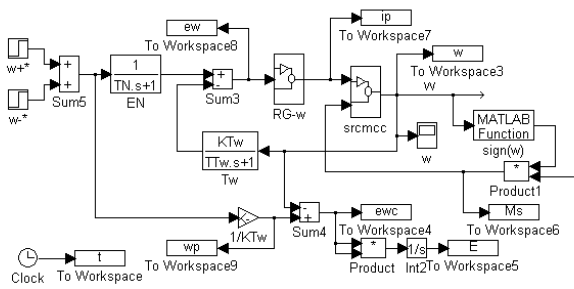


Fig. 5 Simulink diagram for DC control systems

In the diagram from Fig. 5 the current control system is modeled in the block srcmcc. The diagram allows transient analysis fro different load torques and functioning regimes.

2.4 Transient Regime Characteristics

The verification of the speed control system designed with the above methods was done using a transient regime described with the equations:

$$t=0,\ M_s=0,\ \Omega^*(t)=\Omega_b^*\sigma(t);$$
$$t=t_M,\ \Omega(t)=\Omega_b,\ M_s(t)=M_{sN}\sigma(t). \quad (2)$$

The current and speed transient characteristics for the regime (2) are presented in Fig. 6.

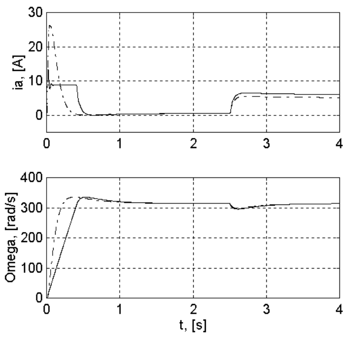


Fig. 6 Transient characteristics of the DC designed speed control system

The characteristics for linear control system, without limitations, are presented with dash-dot line. The characteristics for the control system with limitations are presented with continuous line.

The quality of the speed control system is analyzed using the following control empirical quality criteria.

2.5 Quality Criteria

The quality criteria are defined for linear systems, with the superposition principle, like in Fig. 7.

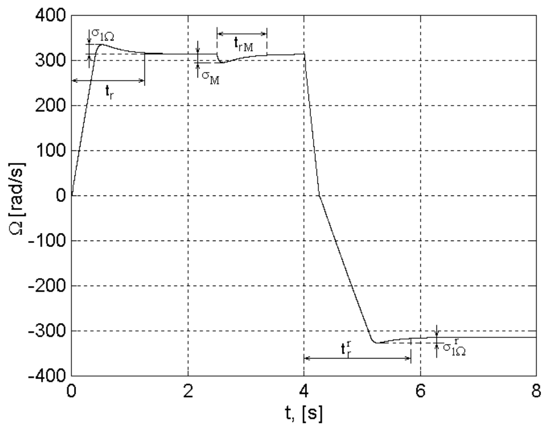


Fig. 7. Diagram for quality criteria definition

1. Quality criteria related to the speed response to the speed reference.

The error in the permanent regime related to the controlled speed Ω:

$$\varepsilon_s = \Omega_s - \Omega_\infty \tag{3}$$

where Ω_∞ represents the permanent regime value of the motor speed and Ω_s is the value at which the speed is stabilized.

The overshoot σ_1 which represents the maximum overpassed of the stationary value Ω_s:

$$\sigma_1\% = \frac{\Omega_{max} - \Omega_s}{\Omega_s}.100\% \tag{4}$$

In the analysis the overshoot at starting $\sigma_{1\Omega}$ and at the reversal σ_{1r} are calculated.

The settling time (the duration of transient regime or the response time) t_r, represents the time period in which the speed $\Omega(t)$ enter the stationary zone, chosen of $\pm0{,}02\Omega_s$, related to the level Ω_s.

Response times for starting $t_{r\Omega}$ and reversal t_{rr} are analyzed.

2. Quality criteria for the speed response at a torque M_s disturbance step.

Error in the stationary regime related to the disturbance

$$\varepsilon_{sM} = |\Omega_{sM}| \tag{5}$$

where Ω_{sM} is the speed value in stationary regime.

The maximum deviation σ_{1M} from the controlled value:

$$\sigma_{1M} = \Omega_{s\max} - \Omega_{sM} \tag{6}$$

The time of disturbance compensation time t_{cM}.

A quadratic criterion:

$$\Im = \int_0^\infty \varepsilon_\Omega^2(t)dt \tag{7}$$

where $\varepsilon_\Omega(t) = \Omega(t) - \Omega_\infty$

The calculation quadratic criterion:

$$\Im = \int_0^{t_s} \varepsilon_\Omega^2(t)dt \tag{8}$$

where $[0, t_s]$ is the duration of the simulation.

3 Fuzzy Control System

3.1 Fuzzy Control Structure

The fuzzy control system has the block diagram from Fig. 8.

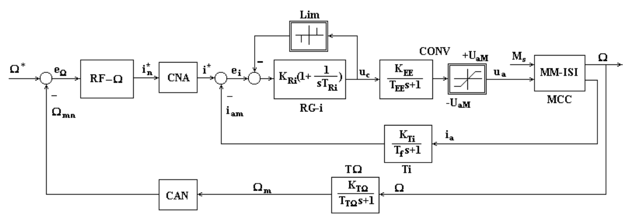


Fig. 8 The block diagram of fuzzy control system

In the place of the linear PI speed controller a fuzzy PI controller RF-Ω is introduced. For the fuzzy control, digital implemented, analogue to digital and digital to analogue converters are introduced: CAN, CNA with the following coefficients: $K_{CAN}=2^{11}/10$ and $K_{CNA}=1/K_{CAN}$. The limitation of the torque (current) reference is the same: $+/-M_M$.

3.2 Fuzzy Controller

3.2.1 Controller Structure

The fuzzy PI controller has the structure from Fig. 9.

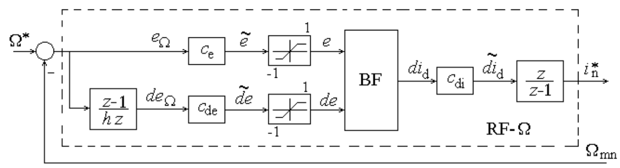


Fig. 9 The block diagram of speed fuzzy controller

In the structure of fuzzy speed controller RF-Ω the elements are: BF is a fuzzy block, c_e and c_{de} are scaling coefficients for the speed error e_Ω and its derivative de_Ω, c_{di} is the fuzzy block output gain c_{di} for the current reference i_n^*. The fuzzy controller has output integration. Two saturation blocks are placed at the fuzzy block inputs. The output of the fuzzy block BF is the defuzzyfied value of the current reference di_d.

3.2.2 Fuzzy Block

The fuzzy block FB has the structure from Fig. 10.

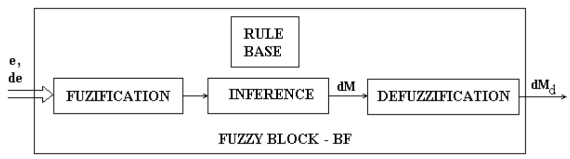


Fig. 10 The structure of fuzzy block

The inputs e and de enter the fuzzyfication interface. An inference with the max-min method is done. The result of the inference is the fuzzy set of the motor torque dM. The torque is considered proportional to the current i. The crisp value of the torque reference dM_d is obtained by defuzzyification. The defuzzyfication is done using the center of gravity method.

Because the fuzzy control system must control speed in a four quadrants torque-speed characteristic, a symmetric rule base, symmetric universes of discussion, for both positive and negative values of the physical variables and symmetric membership functions are chosen.

The inputs e and de enter the fuzzyfication interface. An inference with the max-min method is done. The result of the inference is the fuzzy set of the motor torque dM. The crisp value of the torque reference dM_d is obtained by defuzzyification. The defuzzyfication is done using the center of gravity method.

3.2.3 Operator knowledge

The rule base of the fuzzy speed controller is developed based on the following relation, that characterizes the physical process. The second law of dynamics:

$$J\frac{d\omega}{dt} = M - k_f\,\omega - M_s \tag{9}$$

The relation of comparison between the speed reference and the measured speed:

$$a_w = \Omega^* - \Omega_m \tag{10}$$

where the measured speed Ω_m is considered an instantaneous information about the rotor speed Ω:

$$\Omega_n \propto \Omega \tag{11}$$

The active torque M is instantaneous released by the actuator from the torque reference M^*:

$$M \propto M^* \tag{12}$$

In the design procedure the value of the torque in the permanent regime is unknown, because the value of M_s is unknown. But, the integration at the output of the fuzzy controller solves this problem. The fuzzy controller gives the defuzzificated value of the torque increment dM_d, proportional to the current i.

3.2.4 Rule Base

For a permanent regime the following reasoning is made: "*If* e_Ω =0 *and* de_Ω/dt =0 *then the active torque must match the resistant torque* ($M=M_R$), *then the torque increment must be zero:* ΔM=0." This will be the first rule, or the rule for the permanent regime. For the other positive and negative values of e_Ω and de_Ω/dt other reasonings may be done, for example: "*If* e_Ω<0 ($\Omega^*<\Omega_m$ *-the speed is greater then the reference*) *and* de_Ω/dt<0 ($d\Omega/dt$>0 - *the speed is increasing*) *then the speed must be decreased, decreasing the active torque, then the torque increment must be negative:* ΔM<0" - rule number 2.

The physical (and fuzzy) variables are: the speed error $e_\Omega=\Omega^*-\Omega_m$, the speed error derivative de_Ω/dt and the torque increment ΔM, (or the current increment Δi). For these variables the following fuzzy variables: *e*, *de* and *dM* (*di*), were chosen. For each of the fuzzy variables three fuzzy values: *N*, *ZE* and *P*, were chosen, corresponding to the above reasoning. With these fuzzy values the complete rule table is written in Tab. 1. The rules are marked from *1* to *9*.

Tab. 1 Rule base

dM		e		
		N	Z	P
de	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

3.2.5 Universes of discourse

The universes of discussion for the fuzzy controller variables are chosen based on the process knowledge - the static characteristic speed-torque defined by the rated and the maximum variable values: Ω_N - the rated speed, M_c the rated torque in a continuous regime, M_M the maximum torque in a transient regime [9]. The speed control system can not give a torque increment ΔM greater then $M_M/5T_a$.

The universes of discussion are presented in Fig. 11.

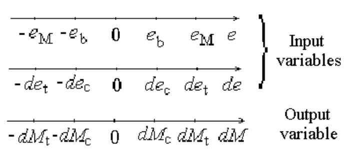


Fig. 11 Universes of discourse

The main values of the universes of discussion are:

$$e_N = K_{CAN} K_{T\Omega} \Omega_N,$$
$$e_M = 2 e_N$$

$$de_c = K_{CAN} K_{T\Omega} (M_N + k_f \Omega_N) / J$$
$$de_M = K_{CAN} K_{T\Omega} (M_M + k_f \Omega_N) / J \tag{13}$$

$$dM_c = \frac{M_N}{5 K_{CNA} K_a T_a}$$
$$dM_M = \frac{M_M}{5 K_{CNA} K_a T_a}$$

The universes of discussion are scaled with the scaling factors: e_b, de_c and dM_N.

The membership functions for the fuzzy variables are presented in Fig. 12.

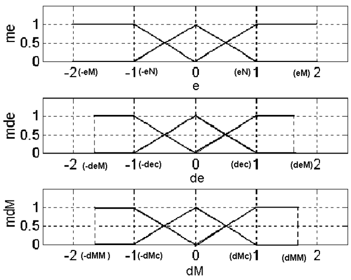


Fig. 12 Membership functions

Absolute values greater then e_N, de_c or dM_N are considered *P* - pozitive (or *N* -negative) with a membership degree equal to 1.

3.2.6 Input-Output Transfer Characteristics

The fuzzy block FB has the following input-output transfer characteristics.

The family of the characteristics $dM_d = f_e(e; de)$, with *de* parameter, for the fuzzy block BF, is presented in Fig. 13.

The family of the characteristics $dM_d = f_{BF}(x_{t1}; de)$, with *de* parameter, is presented in Fig. 14.

The new compound variable is:

$$x_{t1} = e + de \tag{14}$$

The family of the characteristics of the equivalent gain K_{BF} of the fuzzy block defined with the following relation:

$$K_{BF} = K_{BF}(x_{t1}; de) = \frac{dM_d}{x_{t1}}, x_{t1} \neq 0 \tag{15}$$

is presented in Fig. 15.

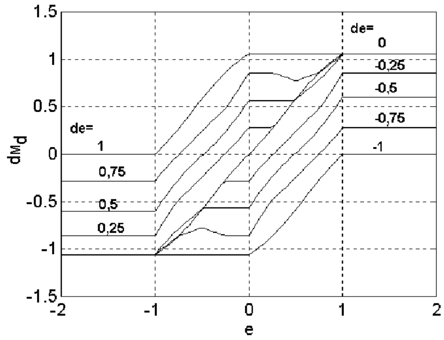


Fig. 13 SISO transfer characteristics

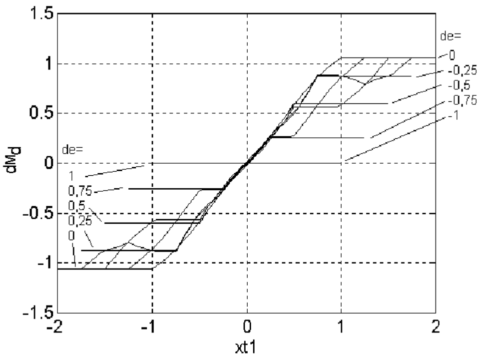


Fig. 14 SISO translated transfer characteristics

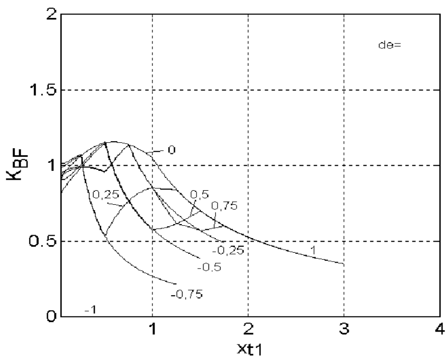


Fig. 15 Gain characteristics

The surface $dM_d = F(e, de)$ of the fuzzy block is presented in Fig. 16.

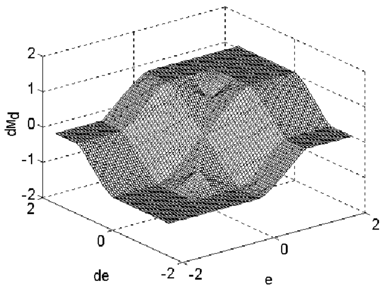


Fig. 16 MIMO transfer characteristic

3.2.6 Algebraic Properties

The fuzzy block FB is an algebraic application with the following properties.

A commutative law:

$$dM_d = F(e, de) = F(de, e) \tag{16}$$

and symmetrical elements:

$$F(-x, x) = F(x, -x) = 0 \tag{17}$$

3.3 Pseudo-Equivalence of Fuzzy Controller

The fuzzy block BF is linearized around the origin and the fuzzy speed controller with integration at the output has the following relation in the z-domain:

$$\begin{aligned} M^*(z) &= \frac{z}{z-1} c_{dM} K_0 [e(z) + de(z)] = \\ &= \frac{z}{z-1} c_{dM} K_0 \left(c_e + c_{de} \frac{z-1}{hz} \right) a_\Omega \end{aligned} \tag{18}$$

where K_0 is the value of the gain of the fuzzy block around the origin:

$$K_0 = \lim_{x_{t1} \to 0} K_{BF}(x_{t1}; 0) \tag{19}$$

and h the sample time.

The transfer function of the fuzzy PI controller becomes:

$$H_{RF}(z) = \frac{M^*(z)}{e_\Omega(z)} = \frac{z}{z-1} c_{dM} K_0 \left(c_e + c_{de} \frac{z-1}{hz} \right) \tag{20}$$

And in a continuous time form:

$$\begin{aligned} H_{RF}(s) &= \frac{M^*(s)}{e_\Omega(s)} = H_{RF}(z)\Big|_{z=\frac{1+sh/2}{1-sh/2}} = \\ &= \frac{c_{dM} K_0}{h} \left(c_{de} + \frac{h}{2} c_{de} \right) \left[1 + \frac{c_e}{(c_{de} + c_e h/2)s} \right] \end{aligned} \tag{21}$$

An equivalence of $H_{RF}(s)$ with a PI linear controller may be notice:

$$H_{R\Omega}(s) = K_{R\Omega} \left(1 + \frac{1}{sT_{R\Omega}} \right) \tag{22}$$

The coefficient of two transfer functions may be equalized and the following equations are obtained:

$$\begin{aligned} K_{R\Omega} &= \frac{c_{dM} K_0}{h} \left(c_{de} + \frac{h}{2} c_{de} \right), \\ T_{R\Omega} &= \frac{c_{de} + hc_e/2}{c_e} \end{aligned} \tag{23}$$

The relations for the fuzzy controller design, considering $K_{R\Omega}$ and $T_{R\Omega}$ given, may be obtained from the above relations:

$$\begin{aligned} c_e &= \frac{hK_{R\Omega}}{c_{di} K_0 T_{R\Omega}}, \\ c_{de} &= c_e (T_{R\Omega} - h/2) \end{aligned} \tag{24}$$

The problem in this design procedure is to choose the value of the gain factor c_{dM}.

3.4 Stability Analysis

3.4.1 Control Structure for Stability Analysis

For stability analysis the fuzzy control system may be presented like in Fig. 17.

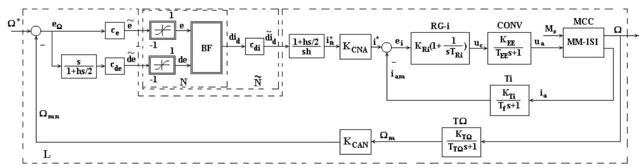


Fig. 17 The structure for stability analysis

A linear part L, containing the motor, the converter, the sensors and the dynamic parts of the fuzzy controller and a nonlinear part N, containing the fuzzy block and the input saturations are emphasized. The nonlinear part has the gain coefficient c_{di} incuded and formed a compensated nonlinear part $\tilde{N}$. In the following paragraph the method to chose the c_{di}, assuring absolute internal stability of the control system using is presented.

The structure from Fig is treated in the frame of nonlinear stability analysis using the circle criterion, as it is presented in Fig. 17.

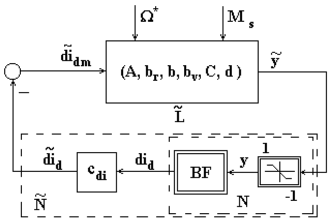


Fig. 18 Structure for circle criterion

The nonlinear part has two input variables:

$$y = [y_1 \;\; y_2]^T = [e \;\, de]^T \qquad (25)$$

and one output variable:

$$\tilde{di}_d = c_{di} f_{BF}(y) \qquad (26)$$

Using the compose x_{t1}:

$$x_{t1} = [1 \quad 1] y = e + de \qquad (27)$$

and the gain:

$$K_{BF}(x_{t1}; de) = \frac{f_{BF}(e, de)}{x_{t1}}, \; pt. \; x_{t1} \neq 0 \qquad (28)$$

the variable di_d is expressed as:

$$K_{BF}(x_{t1}; de) = \frac{f_{BF}(e, de)}{x_{t1}}, \; pt. \; x_{t1} \neq 0 \qquad (29)$$

$$di_d = \begin{cases} K_{BF}(x_{t1}; de) x_{t1}, & pt. \;\; x_{t1} \neq 0 \\ 0, \;\; pt. \; x_{t1} = 0 \end{cases}$$

The characteristics $di_d = f(x_{t1};\; de)$, presented in Fig. have the sector property:

$$0 \leq K_{BF}(x_{t1}; de) \leq K_M \qquad (30)$$

to be in the I and III quadrants including the Ox axis. And the input-output characteristic of the nonlinear part is presented in Fig. 19.

To change this characteristic not to contain the Ox axis and to assure stability a non-linear correction is recommended.

This correction is presented in Fig. 20.

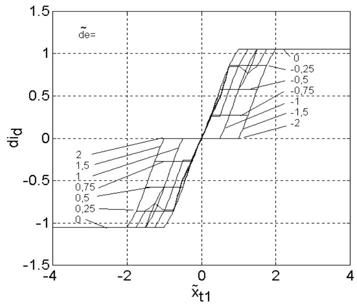


Fig. 19 The input-output characteristic of the nonlinear part including the Ox axis

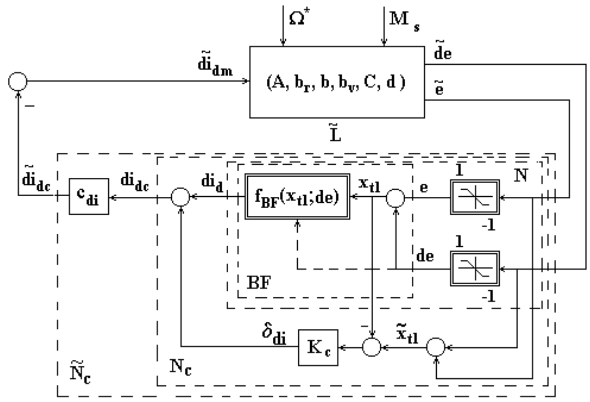


Fig. 20 The control structure with the correction

To accomplish the condition for the sector in the I and III quadrant without the Ox axis for the nonlinear part and to assure stability the correction is made with summing at the output of the fuzzy block a quantity δ_{di}:

$$\delta_{di} = K_c[(\tilde{e} - e) + (\tilde{de} - de)] = K_c(\tilde{x}_{t1} - x_{t1}) \qquad (31)$$

The result is:

$$di_{dc} = f_{\tilde{N}}(\tilde{e}, \tilde{de}) = di_d + \delta_{di} \qquad (32)$$

An example of transfer characteristic for K_c=0,1 is presented in Fig. 21.

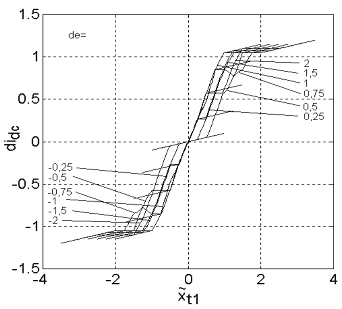


Fig. 21 The corrected transfer characteristic

3.5 Quasi-Fuzzy Controller

After the correction of the input-output characteristic of the fuzzy block the fuzzy PI controller from Fig. 22 results.

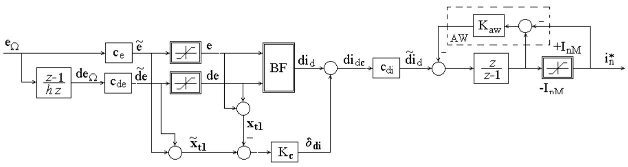


Fig. 22 The structure of quasi fuzzy controller

A quasi fuzzy structure may be notice, in which in parallel with the fuzzy block FB a linear structure is introduced. The correction is nonlinear.

The controller has also an anti wind-up circuit.

3.6 Scaling Coefficients

The scaling coefficients were chosen after some iterative steps, using the quality criteria of the transient characteristics of the speed fuzzy control system at a step speed reference. The speed scaling coefficient c_e had the same value $c_e=1/e_M$. The first value of the derivative scaling coefficient was $c_{de}=1/de_M$. The first value of output scaling coefficient was computed using the relation (…). The second value of c_{de} was computed using the relation (…). The adopted solution contains the values of the scaling coefficients from the sixth step. The transient characteristics obtained in the process of choosing the scaling coefficients are presented in Fig. 23.

The value of c_{dM} is the maximum value of the torque increment:

$$c_{dM\,\max} = M_M^* \tag{33}$$

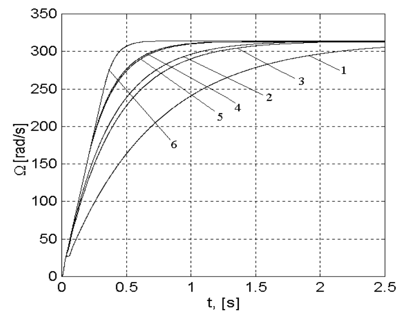


Fig. 23 The transient characteristics for scaling coefficients determination

The value of c_{de} was decreased to the final value from the sixth step. Decreasing more this scaling coefficient the fuzzy control system becomes unstable.

3.7 Modelling and Simulation

A Simulink diagram was developed for modelling and simulating control systems of d.c. drives based on fuzzy logic. It is presented in Fig. 24.

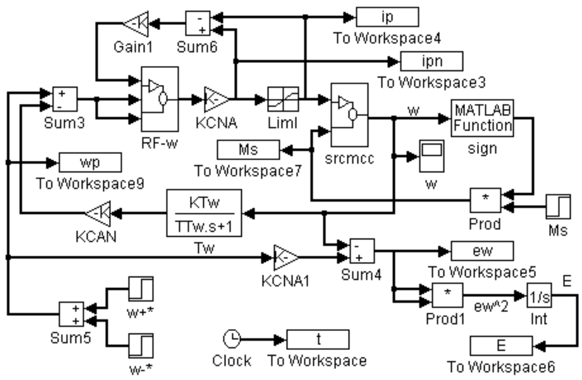


Fig. 24 Simulink diagram for modeling and simulating fuzzy control systems of d. c. drives

The quasi-fuzzy controller is modeled in Simulink with the block diagram from Fig. 25.

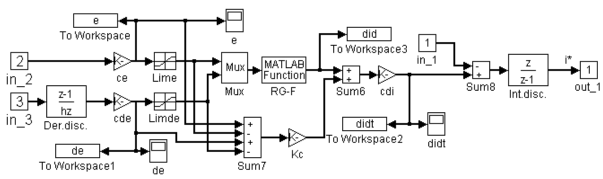


Fig. 25 Simulink block diagram for fuzzy controller

Time domain analysis were made using this simulation models transient. Some results are presented as follows.

3.7 Transient Characteristics

3.7.1 Fuzzy Control

Simulations are made for both control systems, conventional and fuzzy, with tuned parameters: J and k_f and detuned parameters: J^d=2J and k_f^d=2k_f. In the second case an error at the parameter identification is assumed. Three regimes were simulated. The transient characteristics for the current and speed are presented in Fig. 26, 27, 28.

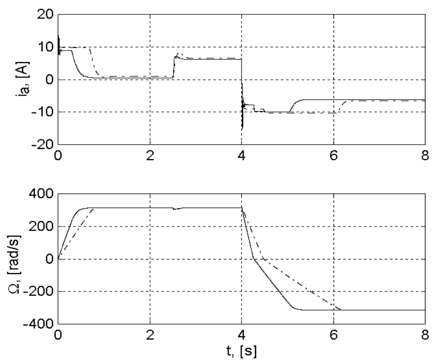


Fig. 26 Transient characteristics for 1st study case

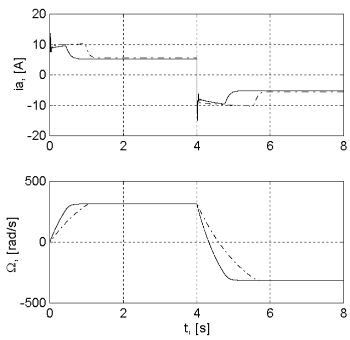


Fig. 27 Transient characteristics for 2nd study case

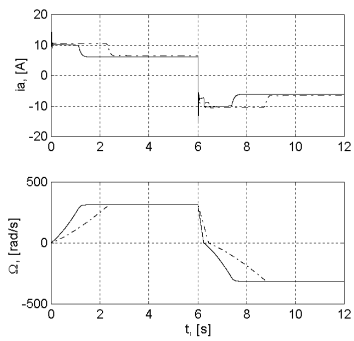


Fig. 28 Transient characteristics for 3rd study case

With continuous line are represented the characteristics for fuzzy control, and with dash-dot line are represented the characteristics for conventional control. The regime consists in starting the process unloaded at t=0 with a constant the speed reference Ω*=314 rad/s. At the time 2,5 s a constant load torque M_s of M_N=3 Nm, in the range of the rated process torque, is introduced.

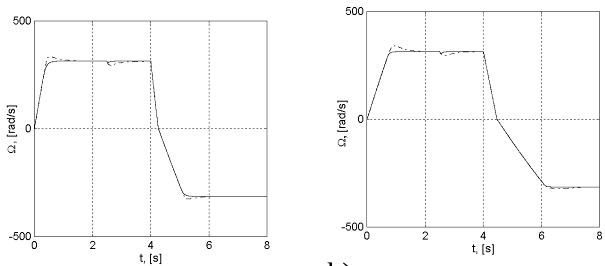
At the time 4 s the speed is reversed, at Ω*=-314 rad/s, maintaining the constant load torque: M_s=$M_N$sign(Ω).

The second regime consists in starting the process loaded at t=0, with a constant the speed reference Ω*=314 rad/s and a load torque M_s=k_sΩsign(Ω). At the time 4 s the speed is reversed, at Ω*=-314 rad/s, maintaining the load torque.

The third regime consists in starting the process loaded at t=0, with a constant the speed reference Ω*=314 rad/s and a load torque M_s=(k_1+k_2Ω)/Ω. At the time 4 s the speed is reversed, at Ω*=-314 rad/s, maintaining the load torque.

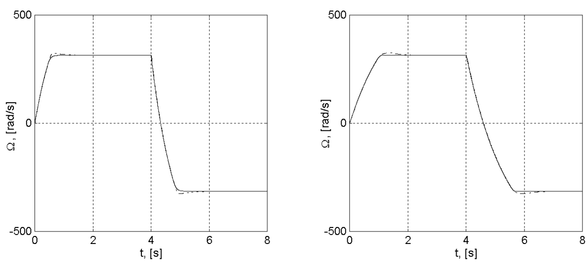
3.7.2 Comparisons

With the transient characteristics obtained for linear and fuzzy control some comparisons may be done. Comparative characteristics for linear and fuzzy control are presented in Fig. 29, 30, 31, for the three study cases 1, 2, 3, for tuned a) and detuned b) parameters.



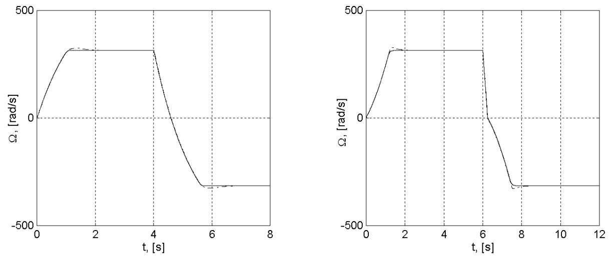
a) b)

Fig. 29 Speed in the 1st case



a) b)

Fig. 30 Speed in the 2nd case



a) b)

Fig. 29 Speed in the 3rd case

3.8 Quality Criteria

Based on a comparative analysis of the speed performance criteria the following may be presented:

- The overshoot of the fuzzy control system for speed reference is zeros at start and at the reversing.
- The settling time for speed reference at start and reversing of the fuzzy control system is smaller.
- If a zero overshoot for the conventional control is designed its settling time will be greater.
- The deviation of speed for perturbation of the fuzzy control system is smaller then in the conventional case.
- The integral criterion has smaller value for fuzzy control.
- The performance criteria of the fuzzy control in the case of detuned parameters are sensitive better then the performance criteria for conventional control.
- So, the fuzzy control system is more robust at the identification errors then the convention control system.

Tab. 2 Values of quality criteria for conventional (c) and fuzzy (f) control, for three torque types 1, 2, 3, for tuned (a) and detuned (d) parameters

Analysis case	$\sigma_{1\Omega}$ [%]	$t_{r\Omega}$ [s]	σ_{1M} [%]	t_{rM} [s]	σ_{1r} [%]	t_{rr} [s]	$\Im$ 10^{-5}	$\Delta\sigma_{1\Omega}$ [%]	$\Delta\sigma_{1M}$ [%]	$\Delta t_{r\Omega}$ [s]	Δt_{rM} [s]
1-c-a	6,7	1	6,1	0,6	4,1	1,5	1,1	6,7	2,3	0,5	0,46
1-f-a	0	0,5	3,8	0,14	0	1,2	1,03				
1-c-d	8,3	1,5	6,1	0,65	4,1	3	2,0	8,3	2,3	0,7	0,51
1-f-d	0	0,8	3,8	0,14	0	2,2	1,89				
2-c-a	2,9	0,9	-	-	4,2	1,3	1,8	2,9	-	0,3	-
2-f-a	0	0,6	-	-	0	0,9	1,04				
2-c-d	3,8	1,7	-	-	4,2	2,3	2,0	3,8	-	0,65	-
2-f-d	0	1,05	-	-	0	1,6	1,9				
3-c-a	4,8	1,6	-	-	4,8	2	1,6	4,8	-	0,3	-
3-f-a	0	1,3	-	-	0	1,5	1,52				
3-c-d	2,9	3,2	-	-	2,9	3,5	3,0	2,9	-	0,9	-
3-f-d	0	2,3	-	-	0	2,8	2,87				

4 Implementation

4.1 Equipment

The fuzzy controller is developed to be implemented with an equipment based on a DSP. The structure of such an equipment is presented in Fig. 27.

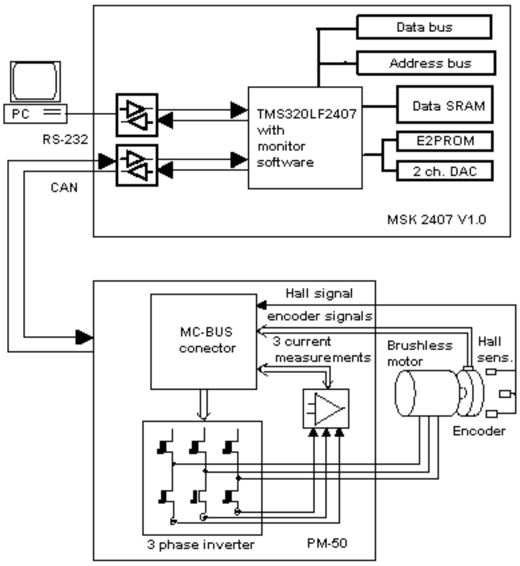


Fig. 27 Control equipment

The control equipment includes: a permanent magnet synchronous motor, with an encoder or a Hall sensor, feed by a 3 phase inverter, a TMS320LF2407 DSP platform with a monitor software.

4.2 Fuzzy Block Implementation

The implementation of the fuzzy block FB may be done using a table interpolation, as a memory. This is the way that assures to minimum time response in the practical implementation of a fuzzy block. Such memory has one output dM_d and two-address a_e and a_{de}. At the output the memory present the real value dM_d memorised at the address (a_e, a_{de}). The addresses are integer. A matrix DM_d with the elements $dM_d(a_e, a_{de})$ corresponds to this memory. The universes of discussion of e and de are digitised in $n_c=2^8+1$ parts. An 8 bit analogue-to-digital converter is presumed satisfactory.

4.3 Transient Characteristics

With this implementation the transient characteristics from Fig. 28 may be obtained.

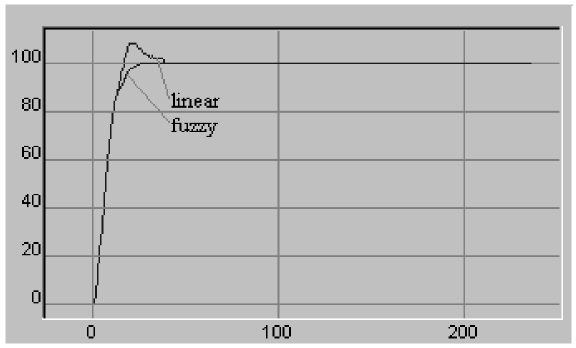


Fig. 28 Speed characteristics

In Fig. 28 two speed responses, for the linear and fuzzy control, are represented. The speed response is faster and the overshoot is zero for the fuzzy control.

5 Conclusions

The paper presents a way to develop speed fuzzy control systems for main electrical drives, using a quasi-fuzzy PI controller, which assures stability of control system and good quality criteria.

Elements of fuzzy controller as rule base, fuzzy values are presented. The controller may use fuzzy systems with a simple rule base with only 9 rules, the max-min inference and the defuzzification with centre of gravity.

Design of fuzzy control system is done based on fuzzy controller transfer characteristics.

To assure stability a correction of fuzzy block is presented. Stability analysis is proof using circle criterion for multivariable non-linear systems.

Relations for pseudo-equivalence of fuzzy PI controller with a linear one are presented.

.Simulink modeling and simulation diagram are presented for conventional and fuzzy control systems.

Transient characteristics for current and motor speed are presented, in different study cases.

Based of transient characteristics some comparisons were made between conventional and fuzzy control systems.

Better quality criteria were emphasized for fuzzy control system.

The fuzzy control system is more robust at error in parameter identification and at disturbance torque influence.

The quasi-controller may be implemented as a fuzzy memory in control systems based on DSPs.

References:

[1] B. K. Bose, Recent Advances and Applications of Power Electronics and Motor Drives, *The 7th WSEAS International Conference on Electrical Power Systems, High Voltage, Electrical Machines*, Venice, 2007.

[2] J.D. Van Wyk, Power Electronics Converters for Motion Control, *Proceedings of the IEEE*, No. 8, 1994.

[3] J. Holtz, Pulsewidth Modulation for Electronic Power Conversion, *Proceedings of the IEEE*, No. 8, 1994.

[4] N. Mohan, W.P. Robbins, T.M. Underland, R. Nilsen, O. Mo, Simulation of Power Electronic and Motion Control Systems - An Overview, *Proceedings of the IEEE*, No. 8, 1994.

[5] G.R. Slemon, Electrical Machines for Variable-Frequency Drives, *Proceedings of the IEEE*, No. 8, 1994.

[6] Leonhard, W. - *Control of Electrical Drives*, Springer Verlag, Berlin, 1985.

[7] I. Boldea, S.A. Nasar, S.A., *Vector Control of A. C. Drives*, CRC Press, Boca Raton, 1992.

[8] R.D. Lorenz, T.A. Lipo, D.W. Novotny, Motion Control with Induction Motors, *Proceedings of the IEEE*, No. 8, 1994.

[9] T.M. Jahnd, Motion Control with Permanent Magnet AC Mashines, *Proceedings of the IEEE*, No. 8, 1994.

[10] H. Le-Huy, Microprocessors and Digital I.C.'s for Motion Control, *Proceedings of the IEEE*, No. 8, 1994.

[11] F. Harashima, Power Electronics and Motion Control - A Future Perspective, *Proceedings of the IEEE*, No. 8, 1994.

[12] Zadeh, L.A. - Fuzzy Sets, *Information and Control*, vol. 8, 1965.

[13] H. R. Buhler, *Reglage par logique floue*, Press Polytechniques et Universitaires Romands, Lausane, 1994.

[14] E. Cox, Adaptive Fuzzy Systems, *IEEE Spectrum*, Feb., 1993.

[15] J.M. Mendel, Fuzzy Logic Systems for Engineering: A Tutorial, *Proceedings of the IEEE*, March 1995.

[16] B.K. Bose, Expert System, Fuzzy Logic and Neural Network Applications in Power Electronics and Motion Control, *Proceedings of the IEEE*, No. 8, 1994.

[17] S. Javadi, Induction Motor Drive Using Fuzzy Logic, *Proceedings of the 7th Conference on 7th WSEAS International Conference on Systems Theory and Scientific Computation*, Vol. 7, Vouliagmeni, Athens, Greece, pp. 264-271, WSEAS, Stevens Point, Wisconsin, USA, 2007.

[18] A. P. Garcia, J.L. Diaz Rodriguez, Fuzzy logic controller design applied to servo-drive systems, *Proceedings of the 9th WSEAS International Conference on Systems*, Athens, Greece, Stevens Point, Wisconsin, USA, 2005.

[19] Singh, B.N.; Singh, B.; Singh, B.P. – Fuzzy Control of Integrated Current-Controlled Converter-Inverter-Fed Cage Induction Motor Drive, *IEEE Transactions on Industry Applications*, Nr. 2, 1999.

[20] S., Bolognani, M. Zigliotto, Fuzzy Logic Control of a Switched Reluctance Motor Drive, *IEEE Trans. on Ind. Applications*, No. 5, Sept., 1996.

[21] Liaw, C.M.; Cheng, S.Y. - Fuzzy Two-Degrees-of Freedom Speed Controller for Motor Drives, *IEEE Trans. on Ind. Electronics*, Nr. 2, 1995.

[22] Lai, M.F.; Nakano, M.; Hsieh, G.C. - Application of Fuzzy Logic in the Phase-Locked Loop Speed Control of Induction Motor Drive, *IEEE Trans. on Ind. Electronics*, Dec., 1996.

[23] D.E. Thomas, B. Armstrong-Helouvry, Fuzzy Logic Control, A Taxonomy of Demonstrated Benefits, *Proceedings of the IEEE*, March 1995.

[24] P. Pivonka, J. Zizka, The Use of Fuzzy PI/PD/PID Controllers in Fuzzy Control, *5th European Congress on Intelligent Techniques & Soft Computing EUFIT'95*, Aachen, 1995.

[25] H. Hellendoorn, Fuzzy Logic and Fuzzy Control, *A Report of Siemens Intelligent Control Systems Lab.*, Germany, 1991.

[26] H. Hellendoorn, C. Thomas, C., On Deffuzification in Fuzzy Controllers, *A Report of Siemens Intelligent Control Systems Lab.*, Germany, 1992.

[27] H.K. Khalil, H. K., *Nonlinear Systems*, Macmillan Pub. Co., New York, 1991.

[28] R. Katoh, T. Yamashita, S. Singh, T. Yamaguchi, Graphical Stability Analysis of a Control System Having 2-Input and 2-Output Fuzzy Controller, *JSME International Journal*, Vol. 39, No. 1, 1996.

[29] G. Langari, M. Tomizuka, Stability of Fuzzy Linguistic Control Systems, *Proc. of the 29th Conference on Decision and Control*, Dec., 1990.

[30] T. Mollers, O. van Laak, S.F. Marinosson, H.J. Wenz, Stability of Fuzzy Systems Based on an Approximation Argument, *7th European Congress on Intelligent Techniques & Soft Computing EUFIT'99*, Aachen, 1999.

[31] T. Scheel, H. Kiendl, Stability Analysis of Fuzzy and Other Nonlinear Systems Using Integral Lyapunov Functions, *5th European Congress on Intelligent Techniques & Soft Computing EUFIT'95*, Aachen, 1995.
[32] R. Schafers, P. Krause, Stability Analysis of Dynamic Fuzzy Systems, *7th European Congress on Intelligent Techniques & Soft Computing*, Aachen, 1999.
[33] H.O. Wang, K. Tanaka, M.F. Griffin, An Approach to Fuzzy Control of Nonlinear Systems: Stability and Design Issues, *IEEE Trans. on Fuzzy Systems*, Feb., 1996.
[34] C. Volosencu, On Some Algebraic Properties of Fuzzy Controllers, *Proceedings of the Int. Conf. On Artificial Intelligence, IC-AI'02*, Las Vegas, NV, CSREA Press, SUA, 2002, pp. 584 – 587.
[35] T. L. Dragomir, C. Volosencu, Some Ways to Implement Fuzzy Controllers, *Revue Roumaine des Sciences Techniques, Serie Electrotechnique et Energetique*, Tome 45, 2000, no. 2, July, 2000.
[36] C. Volosencu, A Method to Assure Stability of Some Fuzzy Controllers, *Proceedings of the Int. Conf. On Artificial Intelligence, IC-AI'02*, Las Vegas, NV, CSREA Press, 2002, pp. 563 – 568.
[37] C. Volosencu, Stability Analysis of a Speed Fuzzy Control System for Electrical Drives, *The 7-th European Congress on Intelligent Techniques and Soft Computing EUFIT'99*, ELITE-Foundation, Aachen, 1999.
[38] C. Volosencu, Demonstration of the Robustness of the Fuzzy Speed Control System at Parameter Identification Errors, *Power Electronics and Machine Control Pemc'98 Conference*, Prague, 1998.
[39] C. Volosencu, Speed Control of Electrical Drives, Based Upon Fuzzy Logic – A Synthesis, *Proceedings of the European Control Conference ECC'99*, Karlsruhe, 1999.
[40] C. Volosencu, Some Consideration about Using Fuzzy Logic for Speed Control of Electrical Drives, *The 7-th European Congress on Intelligent Techniques and Soft Computing EUFIT'99*, ELITE-Foundation Aachen, 1999.
[41] C. Volosencu, Speed Control of a Permanent Magnet Synchronous Motor, Based on a Quasi-Fuzzy Controller, *Proceedings of the 10th European Conference on Power Electronics and Applications*, *EPE2003*, Toulouse, 2003.
[42] C. Volosencu, Fuzzy Control of Electric Drives, *Proceedings of the WSEAS International Conference*, Santander, 2008.