METHOD OF COMPUTATIONAL INTELLIGENCE IN POWER ELECTRONICS

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Abstract: The design of fuzzy logic controllers used to linearize the family of external characteristics of DC-DC converters that work in discontinuous-conduction mode is described in this paper. Simulation study with centered triangular, trapezoidal and Gaussian fuzzy sets justify the choice of triangular membership functions, except the limits of the universe of discourse where Gaussian membership functions suit better. Results demonstrate that fuzzy logic control is a good alternative for conventional control methods. Compared to other intelligent control techniques, the heuristic fuzzy logic algorithm is faster because for any given input data, it processes structured knowledge using only four valid rules from the whole rule base.

1. INTRODUCTION

DC-DC converters are used either in DC-motor drive applications (input voltage U_1 remains constant during the converter operation and output voltage U_2 is controlled by adjusting the duty ratio D) or in regulated switch-mode DC power supplies (U_1 may fluctuate, but U_2 is kept constant by adjusting the duty ratio D) [Mohan et al. 1989]. Discussing only about DC-motor drive applications, speed regulation system diagram includes the speed controller, the current controller and the linearization controller for the family of external characteristics of DC-DC converters working in discontinuous-conduction mode [Radoi et al. 1997]. Linearization is claimed by performant real-time speed control systems for DC induction motors, that needs high precision and low computing time.

The paper focuses only on fuzzy linearization controllers designed to work together with step-down (Buck), step-up (Boost) or step down-up (Buck-Boost) fundamental or derived topologies of DC converters that are usually used to supply DC motors. The 3 fundamental topologies are represented in Fig.1.

DC-DC converters may operate in 3 conduction modes [2]:

1) <u>continuous-conduction mode:</u>

$N=D$ (for Buck converter) (1)

$N=1/(1-D)$ (for Boost converter) (2)

$N=D/(1-D)$ (for Buck-Boost converter) (3)

where: $N= U_2 / U_1$ - equivalent transformer ratio (4)

$D= t_{on} / T$ - duty ratio of the switch CS (5)

$f=1 / T$ - the switching frequency (6)

2) <u>boundary between continuous and discontinuous conduction,</u> with N having the same expressions as in continuous-conduction mode and where $I_{2n,B}$ – normalized average load current in boundary mode, I_{2B} - average load current in boundary mode and $I_{2B,max}$ - maximum of I_{2B} are tied together by equations:

$$I_{2n,B} = I_{2B} / I_{2B,max} = 4D(1-D) \quad (7)$$

$$I_{2B,max} = U_1 / 8fL \quad (8)$$

3) <u>discontinuous-conduction mode:</u>

$$N = D^2 / \left(D^2 + \frac{1}{4} I_{2n} \right) \text{ (for Buck converter)} \quad (9)$$

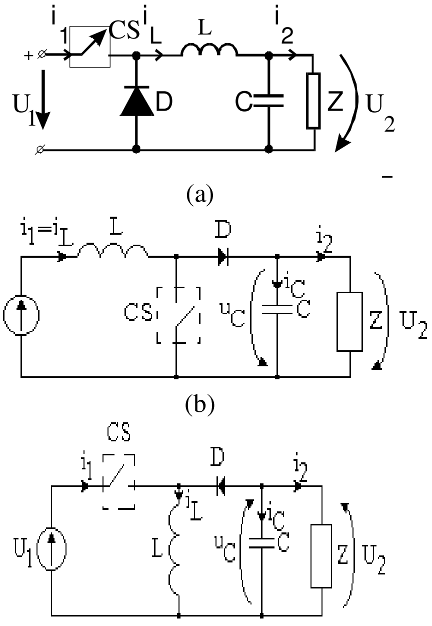
$$N = 1 + 4D^2 / I_{2n} \text{ (for Boost converter)} \quad (10)$$

$$N = 4D^2 / I_{2n} \text{ (for Buck-Boost converter)} \quad (11)$$

where: $I_{2n} = I_2 / I_{2B,max}$ (12)

I_2 – average load current;

I_{2n}- normalized average load current.

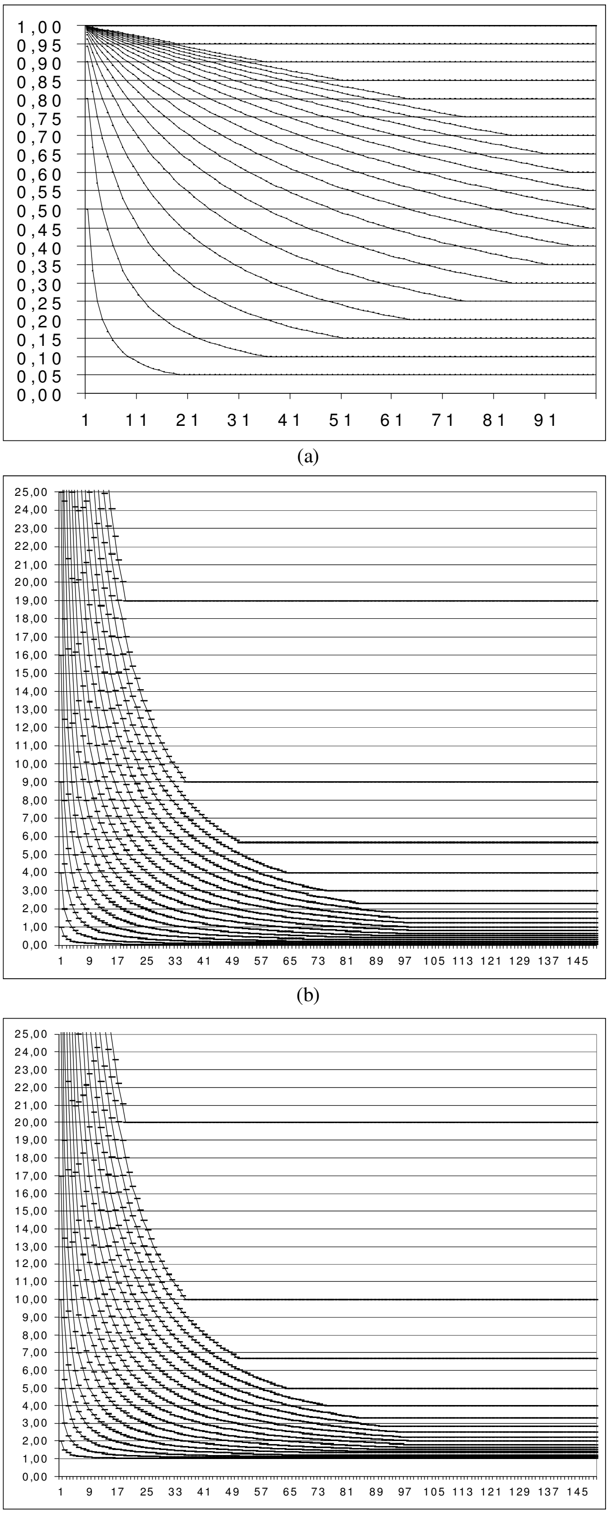


(a)

(b)

(c)

Fig.1. The fundamental topologies of DC-DC converters:
(a) Buck topology of DC-DC converter;
(b) Boost topology of DC-DC converter;
(c)Buck-Boost topology of DC-DC converter



(a)

(b)

(c)

Fig.2. Plots the family of external nonlinear characteristics for: (a) Buck DC-DC converter, (b) Boost DC-DC converter, and (c) Buck-Boost DC-DC converter

Based on equations (1) ÷ (12), Fig.2 plots the DC-DC external family of converter's characteristics $N = U_2/U_1$ as a function of $100*I_{2n}$, in all modes of operation, for a constant U_1, for various values of parameter duty ratio starting down with D=0 and ending up with D=1, with a step of 0.05.

The non-linear characteristics in discontinuous-conduction mode affect the gain of the control loop. If, for example, the loop gain is made optimum at continuous-conduction mode, the lower gain at discontinuous-conduction mode will make the loop response sluggish. On the other hand, if the gain is optimized for discontinuous-conduction mode, at a certain operating point, the loop will tend to be unstable at continuous-conduction mode. The motor will have a bad functional behavior during the discontinuous-conduction mode, so it is better to avoid this mode of conduction.

The solution is to linearize the converter's nonlinear characteristic e.g. to extend the characteristic of the continuous-conduction mode over the discontinuous-conduction mode [Souse et al. 1994].

2. FUZZY LINEARIZATION OF THE EXTERNAL CHARACTERISTICS FAMILY

The linearization can be done using two different methods:

- the conventional control (usually PI or PID type), where we need the accurate mathematical model of the DC-DC converter;
- the fuzzy control, where a mathematical model is not necessary because the rule base imbeds the experience and the intuition of the operator, designer or researcher.

Comparing the two methods, papers on power electronics applications [Sousa et al. 1994], [Bose 1995], [Tremaine 1994], arrived to the same general conclusion that replacing PI classical controllers with fuzzy controllers better parameters of the transient response for the closed sped loop are obtained: rise time, overshot, speed drop and recovery time.

In this paper, in order to obtain an equivalent transformer ratio N as constant as possible, which implies a constant DC motor speed, fuzzy linearisation controller was design according to Ohmae linearisation method [Ohmae et al. 1980]. Fundamentally, duty ratio D is adjusted (added / subtracted) with a value DeltaD according to I_{2n} variation.

The fuzzy control algorithm for linearization [Buhler 1994], [Jager 1995],[Cox 1994],[Ross 1995] can be summarized as follows:

I. Fuzzification

1) normalize the universes of discourses of the chosen fuzzy variables: in our case, the fuzzy variables and their universe of discourse are: I_{2n} (between 0 and 1), D (between 0.05 and 0.95) and DeltaD (between 0 and 0.7);

2) choose the number and shape of fuzzy sets for fuzzy variables: in our case, we have chosen 7 fuzzy sets for I_{2n}, 9 fuzzy sets for D and 11 fuzzy sets for DeltaD and we have

chosen the shapes that can linearize the external characteristics family for the heuristic rule base, i.e. centered triangular, trapezoidal and Gaussian membership functions shapes;

3) calculate the membership degrees of I_{2n}, N and DeltaD for given values: this step of the general algorithm is automatically done by Fuzzy Logic Toolbox from Matlab [11];

II. Fuzzy inference

4) create the rule base by heuristics from the viewpoint of practical system operation:

5) identify the valid rules stored in the rule base, for the given values of I_{2n} , N and DeltaD: this step of the general algorithm is automatically done by Fuzzy Logic Toolbox from Matlab;

6) according to the MIN-MAX fuzzification method (that we have chosen because we obtain the best results), calculate the membership degrees contributed by each rule Ri using MIN operator and the membership degree of the inference using MAX operator between rules: this step of the general algorithm is automatically done by Fuzzy Logic Toolbox from Matlab;

TABLE 1: FUZZY RULE BASE FOR BUCK CONVERTER

DeltaD		D						
		NB	NM	NS	ZE	PS	PM	PB
I_{2n}	NVB		NM	NVS	PVS	PM	PVB	PVB
	NB	NB	NB	NVS	ZE	PVS	PS	PS
	NM			NM	NVS	NVS	ZE	NS
	NS	NVB	NB	NB	NS	NM	NS	NVB
	ZE			NB	NM	NM	NB	
	PS		NVB	NB	NB	NB	NVB	
	PM			NB	NB	NB		
	PB			NVB		NVB		
	PVB			NVB	NVB	NVB		

TABLE 2: FUZZY RULE BASE FOR BOOST CONVERTER

DeltaD		D						
		NB	NM	NS	ZE	PS	PM	PB
I_{2n}	NVB	NM	NVS	PS	PM	PB	PVB	PM
	NB	NB	NS	ZE	PVS	PS	PS	NS
	NM		NM	NS	ZE	PVS	ZE	NVB
	NS			NM	NS	NVS	NS	NVB
	ZE	NVB	NM		NM	NM	NM	
	PS		NB	NM	NM	NM	NVB	
	PM		NVB	NB	NB	NB		
	PB		NVB			NVB		
	PVB			NVB	NVB	NVB		

TABLE 3: FUZZY RULE BASE FOR BUCK-BOOST CONVERTER

DeltaD		D						
		NB	NM	NS	ZE	PS	PM	PB
I_{2n}	NVB	NB	NVS	PVS	PS	PB	PVB	PM
	NB		NM	NVS	PVS	PS	PS	NVB
	NM		NM	NS	NVS	PVS	NVS	NS
	NS	NVB	NM	NM	NS	NVS	NS	NVB
	ZE			NM	NM	NM	NB	
	PS		NVB		NM	NM	NVB	
	PM			NB	NB	NB		
	PB		NVB			NVB		
	PVB			NVB	NVB	NVB		

III. Defuzzification

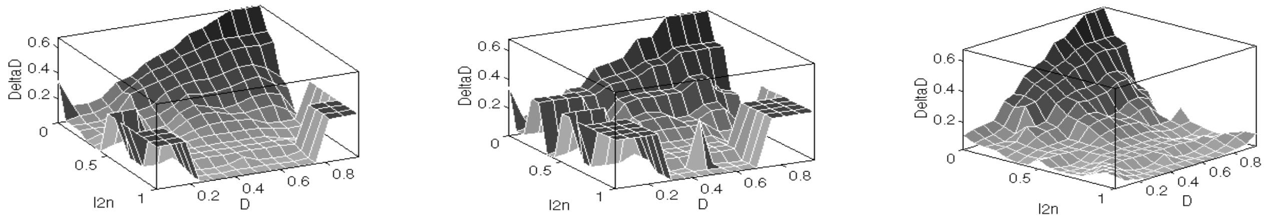
7) calculate DeltaD using different defuzzification methods, based on different calculation formulae for our application []Jang 1995], we tried centroid, bisector, middle of maximum, height and weighted averaged methods and the best method seemed to remain the centroid method.; also, this step of the general algorithm is automatically done by Fuzzy Logic Toolbox from Matlab [MathWorks 1995];

8) find the new D, named D*=D±DeltaD, from the empirical external characteristics $N=N(I_{2n},D)$;

9) verify that $N^{*}= N^{*}(I_{2n},D^{*})$ found for the discontinuous-conduction mode is equal or close to N=D for the continuous-conduction mode.

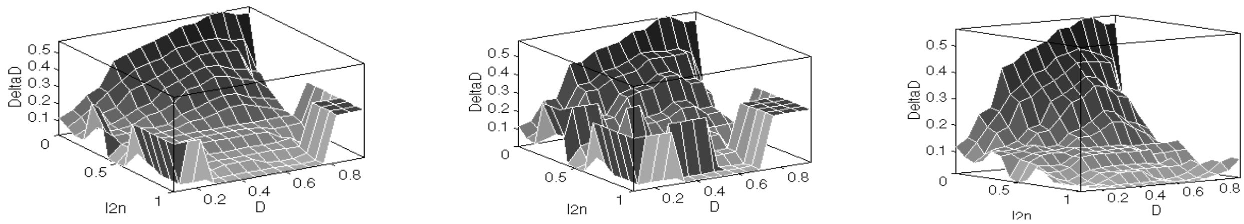
3. SIMULATION RESULTS

Simulation results were obtained using both error tables and control surfaces. Fig.3, Fig.4 and Fig.5 represent the control surfaces for centered triangular, trapezoidal and Gaussian membership functions shapes for DC-DC simulation studied converters.



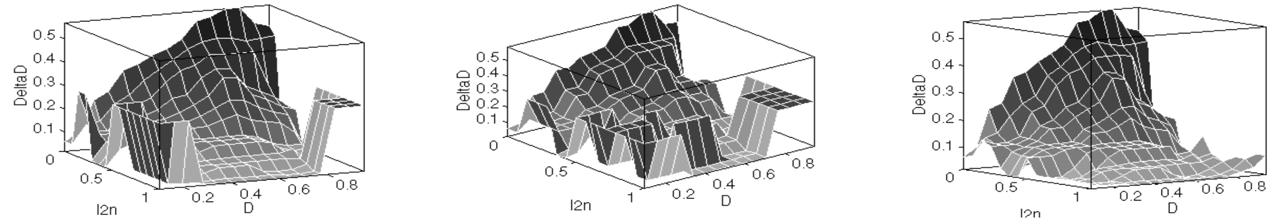
(a) (b) (c)

Fig.3. The control surface for Buck converter: (a) for center triangle membership functions, (b) for center trapezoidal membership functions, (c) for centered Gaussian membership functions



(a) (b) (c)

Fig.4. The control surface for Boost converter: (a) for center triangle membership functions, (b) for center trapezoidal membership functions, (c) for centered Gaussian membership functions



(a) (b) (c)

Fig.5. The control surface for Buck-Boost converter: (a) for center triangle membership functions, (b) for center trapezoidal membership functions, (c) for centered Gaussian membership functions

Some errors of DeltaD compared with the values using equation (8) are plotted in fig. 6. On the horizontal axes is plotted 10*D and on the vertical axes is plotted 1000*error, where error=(DeltaD simulated with Mathlab)-(DeltaD obtained with equation (8), in order to obtain a constant value for N plotted in fig.2. Some linearized curves are plotted in fig.7. Simulation results show that centered triangle membership functions provide smaller errors compared with centered trapezoidal and Gaussian membership functions except the limits of the universe of discourses where Gaussian shapes provide the minimum error.

4. CONCLUSIONS

The design of fuzzy logic controllers for DC-DC converters is described in this paper. Fuzzy controllers are used to linearize the family of external characteristics of Buck, Boost and Buck-Boost converters working in discontinuous-conduction mode occurring at light load and/or high speed. Linearization is claimed by performant speed control systems for dc induction motors that needs high precision and low processing time. A Mathlab simulation study with centered triangular, trapezoidal and Gaussian fuzzy sets justify the choice of triangular membership functions, except the limits of the universe of discourse where Gaussian membership functions suit better. Studies were also made in order to determine the appropriate number for each fuzzy set and to select the deffuzzification method in order to obtain fine linearizations of the non-linear curves. The results demonstrate that fuzzy logic control is a good alternative for conventional control methods, being used particularly in non-linear complex systems. The heuristic fuzzy logic algorithm embeds the intuition and the experience of the operator, designer or researcher and, compared to other intelligent control techniques (expert systems and neural networks) it is faster because it processes structured knowledge using only four valid rules from the whole rule base.

The advantages of fuzzy logic control are general to all fundamental types of DC-DC converters:

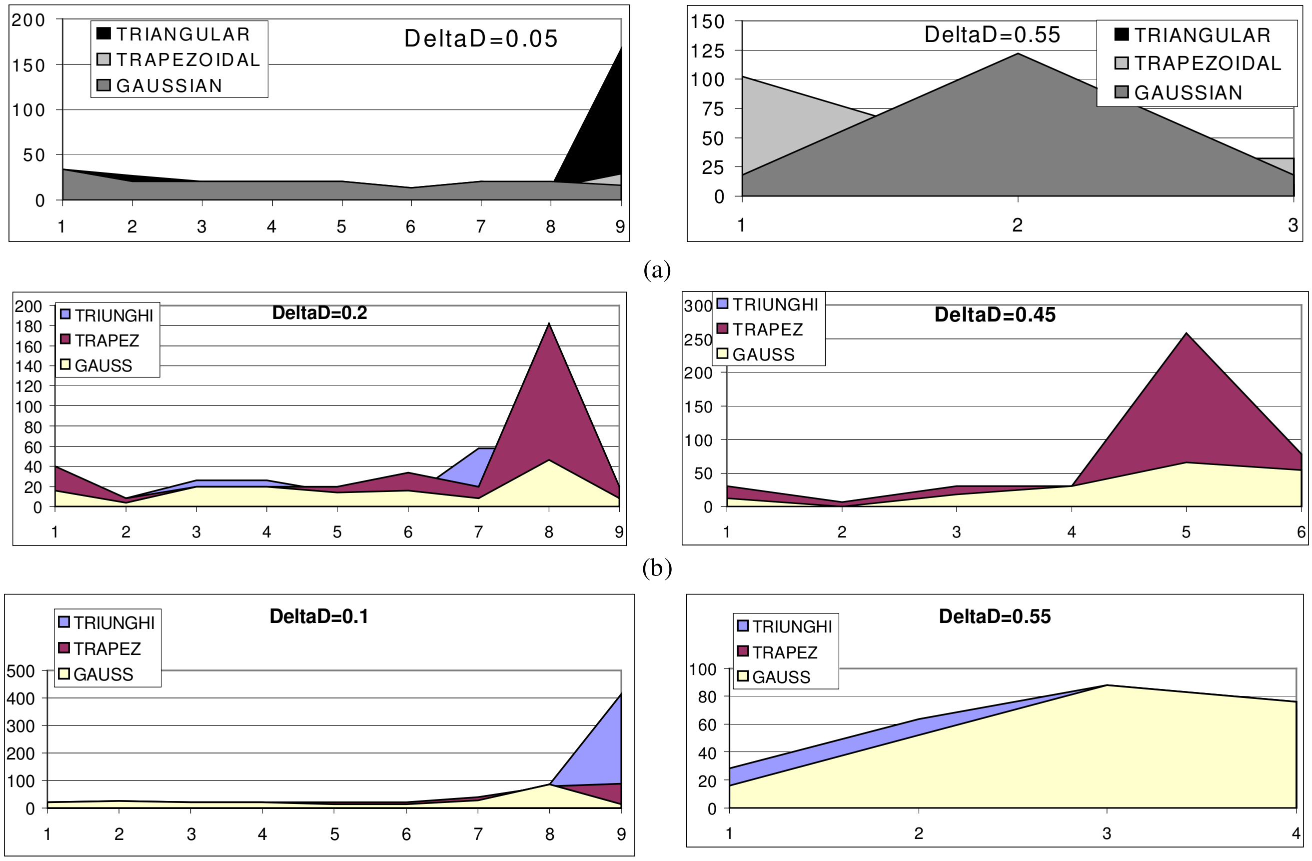
1. centered triangle membership functions are the best to control dc-dc converters used in motor speed control applications (except the limits of the universe of discourses where Gaussian shapes are preferred to obtain a minimum error) and centered trapezoidal membership functions are the worst. This result can also be seen using the control surfaces from fig.3, 4 and 5, where the largest constant area is obtained for the trapezoidal shape;

2. some authors [Buhler 1994] prefer no more than 7 fuzzy sets, simulation results from our present paper and others [Bose 1998] find suitable to choose between 5 and 11 fuzzy sets for each fuzzy variable in order to obtain a good control precision: less means a lower precision and more doesn't improve much the precision but complicates the rule base and make the calculation time longer;

3. centroid defuzzification method is the best for our applications and usually for power electronics applications;

4. for Boost and Buck-Boost converters the equations for discontinuous-conduction mode are different but still non-linear and fuzzy logic control remains an efficient linearization method;

5. fuzzy control is an available alternative for the conventional control, it is simple and inherently adaptive in nature, it doesn't need a mathematical model (but if it exists, it can be useful) and, even if a high speed microprocessor is needed to implement the control, the small number of laws and their simplicity makes it very attractive comparing to expert systems, neural network techniques and conventional-control for very complex or strongly nonlinear systems, where an accurate mathematical model is very difficult or impossible to create.

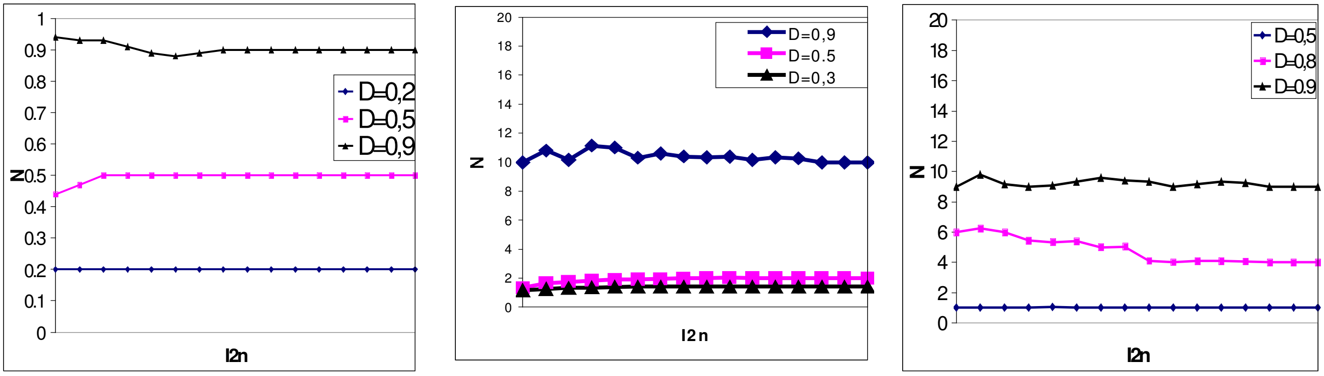


(a)

(b)

(c)

Fig.7. Simulations errors for different parameters D for: (a) Buck converter, (b) Boost converter and (c) Buck-Boost converter



(a) (b) (c)

Fig.8. Linearization curves for: (a) Buck converter (N), (b) Boost converter (10xN), and (c) Buck-Boost converter (10xN)

In spite of the advantages of fuzzy control, the main limitations are:

1. the lack of a systematic procedure for design and analysis of the contro, system, so trial-and error procedure is generally used;
2. iterative approach is taken, which may be time-conduming;
3. the lack of completeness of the rule base, so the controller must be able to give a meaningfull control action for every condition of the process;
4. there are no definite criteria for selection of the shape of membership functions, degree ov overlapping of fuzzy sets and the levels of data acquisition

REFERENCES

Bose B.K., 1998, *Power Electronics and Variable Frequency Drives*, IEEE Power Electronics Society, USA;

Buhler H., 1994, *Reglage par logique floue*, Presses Polytechnique et Universitaire Romandes, Lausanne;

Cox E., 1994, *The Fuzzy Systems Handbook: a Practitioner's Guide to Building, Using and Maintaining Fuzzy Systems*, Academic Press, Inc., New York;

Jager R., 1995, *Fuzzy Logic in Control*, Technische Universiteit Delft, Haga;

Jang R.S., 1995, *Fuzzy Logic Toolbox User Guide*, The MathWorks, Inc.;

Mohan N., Undeland T., Collins W., 1989, *Power Electronics: Converters Applications and Desig"*, Willey Sons Inc., cap.5, pp. 66-76;

Ohmae T., Matsuda T. et al., 1980, *A Microprocessor Controlled Fast response Speed Regulator with dual Mode Current Loop for DCM Drives*, IEEE Trans. Ind. Appl., vol.1A-16, pp.388-394, May/June 1980;

Radoi C., Drogoreanu V., Grigore V., Florescu A., 1997, *Industrial Electronics and Informatics*, Amco Press, Bucharest, pp. 285-313;

Ross T.J., 1995, *Fuzzy Logic with Engineering Applications*, McGraw-Hill, Inc.;

Sousa G., Bose B.K., 1994, *A Fuzzy Set Theory Based Control of Phase-Controlled Converter dc Machine Drive*, in Proceedings of MELECON 1994 , pp. 854-861;

Tremaine B.P., 1994, *Weight the benefits of fuzzy logic vs classical control in a disk-drive spindle,* EDN – The Design Magazine of the Electronics Industry, July 1994, pp.137-145;

- The MathWorks Inc., January 1995, *Fuzzy Logic Toolbox.*