EVOLUTION STRATEGIES IMPROVING A NEW FUZZY LOGIC DESIGN OF A DUTY-CYCLE COMPENSATION CONTROLLER

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Abstract **- The paper presents a new method of designing fuzzy controllers based on interpolation. It also focuses on the advantages of using the combination between fuzzy logic and evolution strategies in design, compared with a simple fuzzy logic design. An application is described i.e. the case of a duty-cycle compensation controller used to linearize the nonlinear external characteristics family of a step-down (Buck) or forward DC-DC converter that supplies DC motors. The controller is additionally introduced in order to confer high precision to speed control systems for DC motors. Similar results were obtained for other basic topologies (Boost, Buck-Boost, and flyback) of DC-DC converters.**

Index Terms **- advanced computational intelligence, Buck converter, fuzzy controller, evolution strategies**

1. INTRODUCTION

Human thinking has both logical and intuitive or subjective sides. The logical side has been developed and utilized, resulting in present advanced von Neumann type computers and *expert systems*, both constituting the *hard computing* domain. However, it is found that hard computing can't give the solution of very complicated problems by itself. In order to cope with this difficulty, the intuitive and subjective thinking of human mind was exploited, resulting the *soft computing* domain (also *called advanced computational intelligence*), a term coined by Lofti Zadeh, the father of fuzzy logic. It includes *neural networks (NN)*, *fuzzy logic (FL)* and *evolutionary computation*, the last gathering *genetic algorithms (GA)* - with related efforts in *genetic programming* and *classifier systems-*, *evolution strategies* and *evolutionary programming* [1], [2], [3]. According to Table I [4], the principal contributions of NN, FL and PR are complementary rather than competitive, so researcher's efforts must focus on using them in combination in order to obtain better designing results. The fuzzy terms for grading in Table I are: good (G), slightly good (SG), slightly bad (SB) and bad (B).

TABLE I
COMPARISONS OF FUZZY SYSTEMS (FS), NEURAL NETWORKS (NN), EVOLUTIONARY COMPUTATION (EC), CONVENTIONAL CONTROL THEORY (CT) AND ARTIFICIAL INTELLIGENCE (AI)

Criteria of comparison	FS	NN	EC	CT	AI
Mathematical model	SG	B	B	G	SB
Learning ability	B	G	SG	B	B
Knowledge representation	G	B	SB	SB	G
Expert knowledge	G	B	B	SB	G
Nonlinearity	G	G	G	B	SB
Optimization ability	B	SG	G	SB	B
Fault tolerance	G	G	G	B	B
Uncertainty tolerance	G	G	G	B	B
Real-time operation	G	SG	SB	G	B

According to TABLE I, evolution strategies can improve the learning ability and especially the *optimization ability* of the simple fuzzy controller during the design stage.

This paper presents a new simple fuzzy logic and fuzzy logic combined with evolution strategies designs of a duty-cycle compensation controller in order to linearize the nonlinear external characteristics family of a step-down (Buck) or forward DC converters that supplies a DC motor. The linearization is needed in order to keep constant the motor speed both during continuous and discontinuous-conduction mode.

2. SPEED CONTROL SYSTEM FOR DC MOTORS

The overall speed control diagram for DC motors (Fig.1) is based upon the classical PI regulation speed control system i.e. it contains two inner basic loops: the external main speed control loop and the internal current control loop that provides fast transient response as well as limits the armature current of the DC motor. In addition, for a high speed precision control system providing a faster transient response, the diagram in Fig.1 is completed with a compensation loop that acts as a *speed preregulator*.

A good dynamic and static behavior of the whole system as well as a high precision of speed regulation are achieved by linearizing input-output characteristics of every functional block contained in the control loop [5]. DC-DC converters supplying DC motors may operate in either continuous or discontinuous mode. During the discontinuous-conduction mode, the nonlinear external family characteristics affect the gain characteristics of the current control loop [6]. 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 mode at a certain operating point, the loop will tend to be unstable at continuous conduction.

This paper focuses only on the compensation controller whose role is to linearize the nonlinear external characteristics of the DC-DC converter.

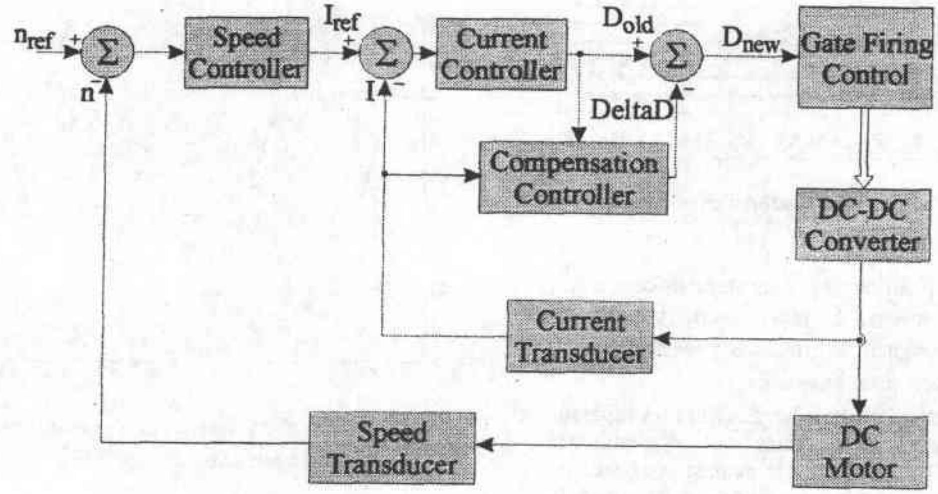

Fig.1. Overall speed control diagram for DC motors

For a DC-DC step-down (Buck) converter or a forward converter with the transformer ratio $n_2 / n_1 = 1$, which is functionally equivalent with a step-down converter (Fig.2), the normalized armature circuit equations [7] for the conduction modes can be given as follows:

1) <u>continuous-conduction mode:</u> $N=D$ if $I_{2n} > I_{2n,B}$

where: $N = U_2 / U_1$ - equivalent transformer ratio of the DC-DC converter, (1)

$D = t_{on} / T$ – duty-cycle of the switch, (2)

$f = 1 / T$ - the switching frequency (3)

2) <u>boundary between continuous and discontinuous conduction mode</u>: $N=D$ if $I_{2n} = I_{2n,B}$

where: $I_{2n,B} = I_{2B} / I_{2B,max} = 4D(1-D)$ - normalized average load current in boundary mode, (4)

I_{2B} - average load current in boundary mode,

$I_{2B,max} = U_1 / 8fL$ - maximum of I_{2B} (5)

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

$$N = D^2 \Big/ \left(D^2 + \frac{1}{4} I_{2n} \right) \text{ if } I_{2n} < I_{2n,B} \qquad (6)$$

where: I_2 - average load current,

$I_{2n} = I_2 / I_{2B,max}$ - normalized average load current.

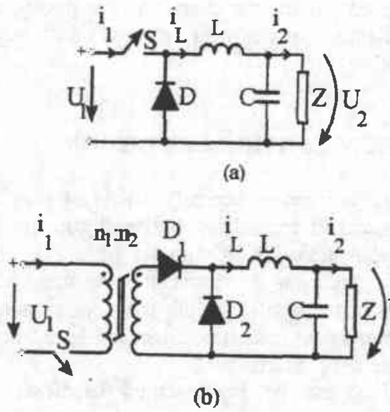

Fig.2. Topology of: (a) Buck converter and (b) forward converter

Based on the equations above, the family of nonlinear external characteristics of Buck converter $N = U_2 / U_1$ as a function of

I_{2n} and with D as parameter in all modes of operation, for a constant U_1, are plotted in Fig.3, for values of duty ratio D starting down with value 0 and ending up with value 1, with a step of 0.05.

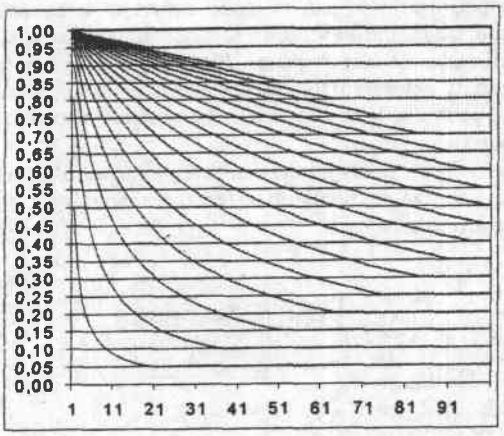

Fig.3. Family of nonlinear characteristics of step-down converter

Fig.3 shows that during the discontinuous-conduction mode, while I_{2n} lowers, the motor speed is increasing because it is proportional with motor's power supply $U_2 = NU_1$ that is proportionally increasing, too.

Among the number of methods suggested to linearize the converter external characteristics at discontinuous conduction mode, the look-up table method suggested by Ohmae et al. [8] appears to be very attractive. It consists in generating an aditional duty-cycle *DeltaD* depending on D and I_{2n} that finally must be added to D (if current I_{2n} is increasing) or subtracted from D (if current I_{2n} is lowered) in order to prolong the characteristics during the continuous-conduction mode over the discontinuous-conduction mode.

3. FUZZY CONTROLLER DESIGN

Speed controller and current controller in Fig.1 may be designed as classical PI controllers, but both simulations and practical applications in DC motors field [9], [10] revealed that by replacing PI classical controllers with fuzzy controllers better results for the transient response represented by parameters: rise time, overshot, speed drop and recovery time were obtained.

Fuzzy controllers can be implemented hardware or software. Hardware, the relation $DeltaD=f(D, I_{2n})$ representing the rule base can be stored in the form of a look-up table in microcomputer's memory. Software, a single subroutine can be accessed by all the fuzzy converters in the control loop, with different data basis.

The paper presents a new method based on learning by example in order to design the fuzzy compensation controller based on zero-order Sugeno fuzzy model [11]. To have a numerical example, let's consider D=0.5. The fuzzification of the input space of I_{2n} is shown in Fig.4 and consists in 5 symmetrical and equidistant triangular membership functions (MFs). The 5 singletons for output DeltaD are chosen according to the desired pairs of data from the data base. Thus, the design of *fuzzy compensation controller* is reduced to *fuzzy interpolation*. Increasing the number of MFs, the error between the desired value and fuzzy value of DeltaD will decrease, but the rule base will increase too and fuzzy controller will tend to become a crisp controller.

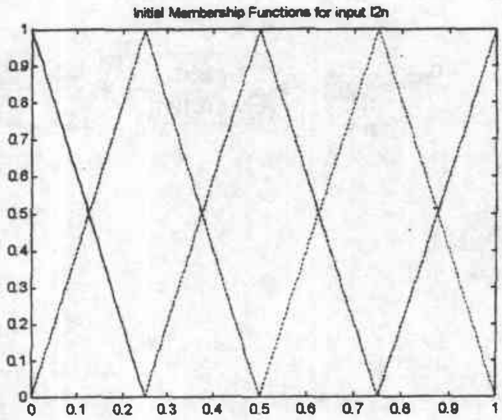

Fig.4. Fuzzification of input space of I_{2n} with 5 symmetrical and equidistant triangle MFs

Simulation used FIS (Fuzzy Inference System) of MatLab. Fuzzy controller has the following parameters:

- one input: I_{2n} and one output: *DeltaD*
- AndMethod: product
- OrMethod: probabilistic Or
- ImplicationMethod: min
- AggregationMethod: max
- DefuzzificationMethod: weighted average
- Rule Base consists in the following 5 rules:
  1. If (I2n is mf1) then (DeltaD is mf5) (1)
  2. If (I2n is mf2) then (DeltaD is mf4) (1)
  3. If (I2n is mf3) then (DeltaD is mf3) (1)
  4. If (I2n is mf4) then (DeltaD is mf2) (1)
  5. If (I2n is mf5) then (DeltaD is mf1) (1)

The result of N linearization is plotted in Fig. 5.

In order to compare different linearization methods presented in this paper, four quality indexes are defined:

1) *Root Mean Squared Error* i.e. an error measure defined by the sum of the squared difference between the actual fuzzy value and the desired value of output *DeltaD* , for a given Number of Training Data (NTD) pairs taken from the data base:

$$RMSE = \sum_{i=1}^{NTD} \sqrt{(DeltaD_{fuzzy} - DeltaD_{desired})^2 \, / \, NTD} \quad (7)$$

2) I_{2n} *domain*, where N has an error bigger than 2% around the $N_{desired}$ value:

$$\left|N_{fuzzy} - N_{desired}\right| \leq 2\% * N_{desired} \quad (8)$$

3) *overshot of N value*, that shows the maximum difference per cent between the actual and the desired value:

$$\sigma[\%] = \frac{N_{desired} - \min N}{N_{desired}} * 100[\%] \quad (9)$$

4) *damp out degree of value N*, that represents the ratio between the second and the first *minN* in equation (9):

$$\delta[\%] = \frac{\sigma_2}{\sigma_1} * 100[\%] \quad (10)$$

For D=0.5, simulation results are: *RMSE*=0.028, I_{2n} *domain*=0.2385, σ=100%,and δ=0%. According to these quality indexes and Fig.5, there are problems of linearization for small values of I_{2n}, when DC motor starts to work. A fuzzy solution to this problem is to increase the number of MFs for input I_{2n}, adding supplementary MFs in I_{2n} subdomain of small values. Similar qualitative results where obtained for different values of D, from 0.1 to 0.9 with a step of 0.1.

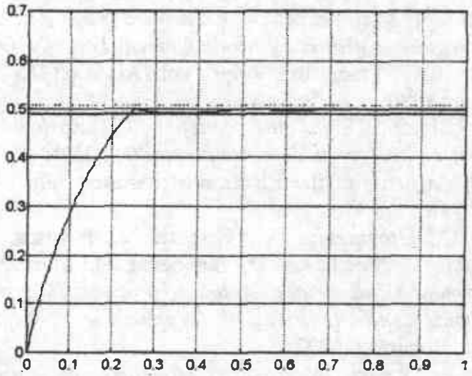

Fig.5. Fuzzy linearization of $N=f(I_{2n})$ for curve D=0.5

4. IMPROVED FUZZY CONTROLLER USING EVOLUTION STRATEGIES

Another solution to improve N linearization is to keep constant MFs number and *tune* them, using the same rule base. An optimization routine based on evolution strategies has been used. with the following characteristics:

- a population of one individual member;
- one chromosome with 25 parameters (3 parameters of the 5 triangular input MFs and 5 parameters of singleton output MFS);
- 5% mutation probability;
- 5% mutation variation around the actual I_{2n} and *DeltaD* values.

The above values have been chosen according to a uniform distribution. After 10000 mutation variations, the new fuzzification of input space of I_{2n} with 5 triangle MFs is plotted in Fig.6.

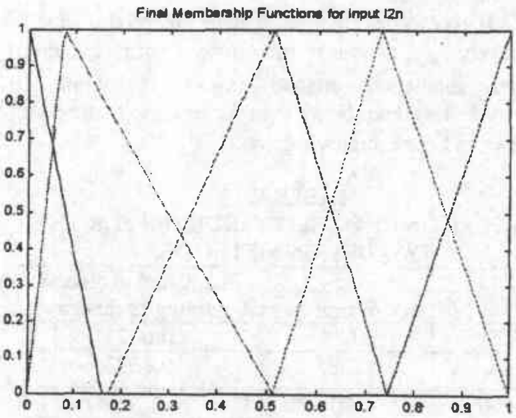

Fig.6. New fuzzification of input space of I_{2n} with 5 MFs triangle MFs

Fig.7 plots the improved N linearization after 10000 mutations. For D=0.5, simulation results are: *RMSE*=0.0024, I_{2n} *domain*=0.1683, σ=13.7508%, and δ=23.8841%. According to Fig.7 and the new quality indexes, by increasing the number of mutations, N linearization curve improves. Better results can be obtained increasing the initial MFs number and/or the mutations number, but the look-up table in microcomputer's memory and/or the computing time are increasing too. A compromise according to the desired quality indexes must be accepted.

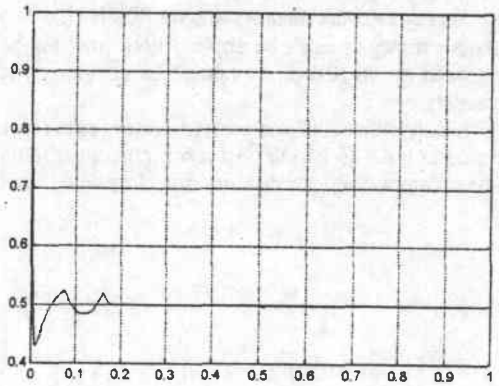

Fig.7. Fuzzy with evolution strategies linearization of $N=f(I_{2n})$ for curve D=0.5

5. CONCLUSIONS

The paper presents two soft computing methods of designing a duty-cycle compensation controller used as a speed preregulator that linearize the family of nonlinear characteristics of Buck or forward converter DC-DC converter necessary in high precision speed regulation systems for DC motors

Table II compares the 2 design methods. *RMSE* (respectively I_{2n} domain) for fuzzy with evolution strategies simulation method model is about 10 (respectively 1.4) times better than fuzzy logic method and indexes σ and δ are improving, too.

TABLE II
COMPARISON OF QUALITY INDEXES FOR THE TWO DESIGN METHODS

	Fuzzy design	Fuzzy and evolution strategies design
RMSE	0.028	0.0024
I_{2n} *domain*	0.2385	0.1683
σ [%]	100	13.7508
δ [%]	0	23.8841

Better results can be obtained increasing the number of MFs and/or using longer the evolution strategies, but the computation time is longer and the results are slowly improving in a longer computation time. A compromise between the time of computation and the precision of designing the fuzzy controller must be accepted.

Similar results were obtained for other basic DC-DC converter topologies (Boost, Buck-Boost, and flyback), showing that fuzzy logic is a very good designing method for nonlinear systems.

A discussion on real-time implementation is also important:

- fuzzy controllers based on triangular MFs shapes have been already hardware implemented with fuzzy processors or software as programs on PCs [12];
- evolution strategies can't be applied until now but in design and not in real-time control, being long time consumers.

The conclusion is that it is necessary a better technology to be created in order to handle fast a big amount of data for real-time computation needed in control systems, fact that will permit to develop this exciting domain of soft computing.

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