Fuzzy Controller for Field-Oriented Robot Drive with Induction Motor

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Abstract: The paper deals with the design and application of a fuzzy controller in a robot drive system with induction machine, fed by a three-mono phased PWM current converter. Fuzzy numbers and their main operations are defined and the structure of a fuzzy speed controller is presented. The advantages offered by a fuzzy controller are demonstrated by simulated results discussed at the end of the paper.

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Introduction

Robot drives with AC machines need complex control systems with long computing time. It is difficult even for powerful microprocessors to meet such requirements. Robot drive systems are non-linear (mechanical load, moment of inertia, etc.) and the performances incumbent on them are great: precision, short response time, large scale of commands (different position controls, speed control, load control). A fuzzy controller is proposed instead of the classical PI one and its advantages are accounted for.

Fuzzy mathematics originated from a development of Boolean mathematics, for modelling intermediate grades of belonging that occur in any concept [6]. Fuzzy has been imagined to reflect the vagueness of human perception and the notion of the level of presumption [3]. A new trend in control engineering from artificial intelligence to expert systems (knowledge-based systems) has opened up. It has also made it possible to develop new types of computers reflecting human cognitive processes.

Fuzzy control is one of the most interesting application areas of fuzzy theory. A first application of fuzzy controller was in small industrial units.Fuzzy controllers used in fast drives applications scored better,particularly in terms of robustness and computing time, than the conventional controllers [1].

Some different configurations are simulated (speed control, position control with and without speed limitation) and a few results are presented and commented.

Control Strategy of the Induction Machine

The robot drive with AC machine control strategy is based on the vector control theory [5], which allows a computation of the control loops by processing direct current data.

The block diagram of the position control system is presented in Figure 1. When only speed control is intended, the position loop and the position controller may be ignored. The field orientation was dictated by the rotor flux phasor. The induction motor is fed by a three-mono-phase current controlled PWM converter. A two-phase model of the induction machine is used for simulation purpose.

On decoupling the active (mechanical) variables from the reactive (magnetic) components, two control loops are obtained, similar to a DC machine with separate field winding. In this case the electromagnetic torque vector, described by the cross product

$$\overline{m}_e = k_{Mr}\left(\underline{\Psi}_r \times \underline{i}_s\right) \tag{1}$$

can be computed from two independent variables, as follows:

$$m_e = k_{Mr}\Psi_r \, i_{sq\lambda_r}, \tag{2}$$

where K_{Mr} is the torque constant and $i_{sq\lambda_r}$ is the active component of the stator-current space phasor.

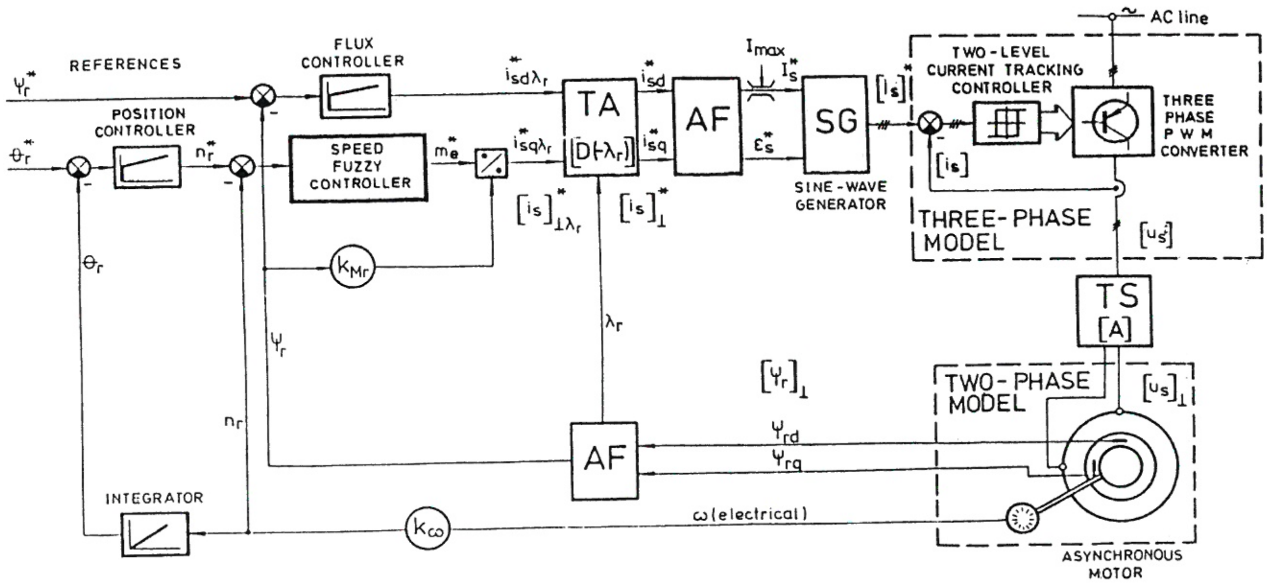

Figure 1. Block Diagram of a Position Control System with Induction Machine.

The flux controller is a classical PI one of which proportional factor K_P is high and which maintains the flux stiff constant. The position controller is a PI one as well, but with a very small integrator character ($K_I = 10^{-3}s^{-1}$). This controller used or not speed limitator. Speed controller, the most important block for the robot drive performances, is a fuzzy controller; it will be described in the next paragraph. This controller output is the imposed electromagnetic torque.

Fuzzy Controller

Many definitions have been given to fuzzy controller [1] ,[2] , [3] ,[6] . We define it as a module, which processes fuzzy data in a fuzzy or non-fuzzy control scheme.

Fuzzy Numbers

There are many ways of representing data in a fuzzy form. A class of fuzzy numbers called triangular fuzzy numbers will be referred. An example is given in Figure 2. This class of fuzzy numbers was used in modelling the control system dealt with in this paper. A triangular fuzzy number (T.F.N) can be defined by a triplet of values (a_1,a_2,a_3). The T.F.N. shown in Figure 2 has the membership function defined as:

$$\mu_A = \begin{cases} 0, & x < a_1, \\ (x-a_1)/(a_2-a_1), & a_1 \le x \le a_2, \\ (a_3-x)/(a_3-a_2), & a_2 \le x \le a_3, \\ 0, & x > a_3. \end{cases} \quad (3)$$

One can also define algebraic operations on the T.F.N. [3]. The basic operation is the linear ordering of fuzzy numbers. Three criteria are known for the T.F.N. If the first criterion does not indicate a unique linear order, then the second and the third criteria should be called in.

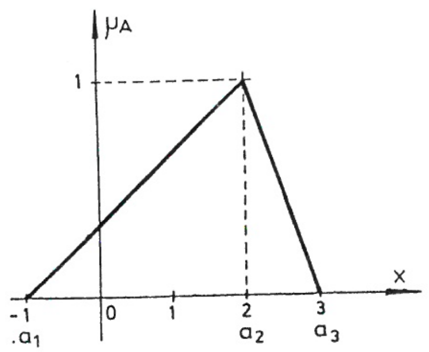

Figure 2. Triangular Fuzzy Number (T.F.N.)

The first criterion is giving up the fuzzy number relative to "x=0" (**"ordinary representative"**) and is invoked by the expression:

$$\hat{A} = (a_1 + 2a_2 + a_3)/4, \quad (4)$$

where $A(a_1,a_2,a_3)$ is the triangular fuzzy number. The second criterion is the **"mode"** of the fuzzy number, defined as:

$$\textbf{mode}(A) = a_2. \quad (5)$$

The third criterion is **"divergence"**, defined for a T.F.N. as:

$$\textbf{divergence}(A) = a_3 - a_1. \quad (6)$$

The following values, namely A(-1,2,3), will be there for the example given in Figure 2,

$$\begin{cases} \hat{A} = (-1+4+3)/4 = 1.5 \\ \textit{mode}\ (A) = 2 \\ \textit{divergence}\ (A) = 4 \end{cases} \quad (7)$$

The two norms which define the rules of fuzzy mathematics, should be observed for defining the basic algebraic operations:

- addition and substraction operations on two T.F.N.s results in a T.F.N.
- multiplication, inverse and division operations on T.F.N.s do not necessarily result in a T.F.N., but they approximate a T.F.N. [3].

Linguistic Variables and Control Rules.

An important step in designing a fuzzy controller will be selecting its linguistic input and output variables and formulating the control rules. In principle, the form of the control rules is the following:

$$\textit{if}\left(X_1(x_i), X_2(x_i), \ldots, X_n(x_i)\right), \textit{ then } C(x_i), \quad (8)$$

where $X_1, X_2, \ldots, X_n$ are input variables, C is the output (command) variable and x_i is a linguistic value.

Usually, electrical drive controls have the inputs error $E = \{e_1, e_2, \ldots, e_{n1}\}$, and the change of error $DE = \{de_1, de_2, \ldots, de_{n2}\}$ and the output is the command $U = \{u_1, u_2, \ldots u_{n3}\}$. In this case (8) can be written:

$$\textit{if}\ \left(\mathbf{E}\ (e_i)\ \textit{and}\ \mathbf{DE}\ (de_j)\right), \textit{ then } \mathbf{U}\ (u_k) \quad (9)$$

where e_i de_j, and u_k are linguistic values.

Currently, control rules are based on a limited set of linguistic values. Table I contains a set of linguistic values as well as their abbreviations when referring to the fuzzy controller, as this paper makes use of.

Table I
Linguistic Values for the Fuzzy Controller

PB = positive big
PM = positive medium
PS = positive small
Z = zero
NS = negative small
NM = negative medium
NB = negative big

Fuzzy numbers are best in symbolizing linguistic values. This justifies our indicating the linguistic variables as fuzzy variables as well. Taking fuzzy numbers as T.F.N., see Figure 2, it is possible that the linguistic values given in Table I are represented in a universe of discourse $x = [-9,9]$. This is shown in Figure 3. Each linguistic value has been attached a triangular fuzzy number which represents its membership function, with $a_2 - a_1 = a_3 - a_2 = 3$.

Design of Fuzzy Controller.

The block diagram of the fuzzy controller is shown in Figure 4. It has three linguistic variables, two inputs, e_0 and Δe_0, and one output u_0.

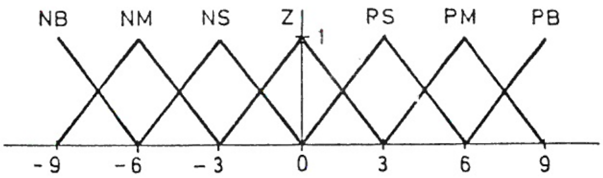

Figure 3. Fuzzy Sets Representing the Linguistic Values of Table I.

The controller has three main parts. First, it is the fuzzification block, which prepares the inputs. A scaling factor is applied to the speed error $e' = \Delta n$ and then transformed from a numerical value into a linguistic value and, later, into a fuzzy number. Mathematically, this is achieved through quantization and limitation. Change of error needs equation $\Delta e' = e'_k - e'_{k-1}$ be applied, where k means the number of steps.

The obtained value is then scaled and fuzzified.

The second part of the controller is the block of inference and composition. Once the control rules known, the fuzzy output value u_0 will result from combining all the fuzzy input values inferred by each control rule.

Practically, a look-up table is produced and the output value is at the intersection of the corresponding values of e_0 and Δe_0.

The third part consists in defuzzification blocks, which transform the fuzzy number u_0 into the corresponding linguistic value and then into a discrete value. The output command m_e^* has two values. The first value is obtained directly by scaling the defuzzified output value u_0.

The second value results from the equation $\Delta u_k = \Delta u_{k-1} + u_0$ and physically represents the change of command. This component assigns a very high value to the command (electromagnetic imposed torque),and so, it is necessary that the value is limited. However, the saturation value must be imposed high enough , in order to avoid the limitation of the current under the value which has already been established by the current limitator. Otherwise the AC machine will not work at full capacity.

-Application to the Robot Drive with AC Machine

The robot drive simulation was based on a two-phase model of the induction motor [4]. The motor rated data are the following:

U_s =220 V stator phase voltage;

I_s =14 A stator phase current;

n =720 rev/min rotor speed

and the parameters:

R_1 =0.719 Ω stator resistance;

R_2 =0.655 Ω rotor resistance;

L_m =0.0947 H mutual inductance.

The mechanical load and the moment of inertia are non-linear (depending on the dynamic configuration of the robot linkages).

The control diagram as simulated in this paper is

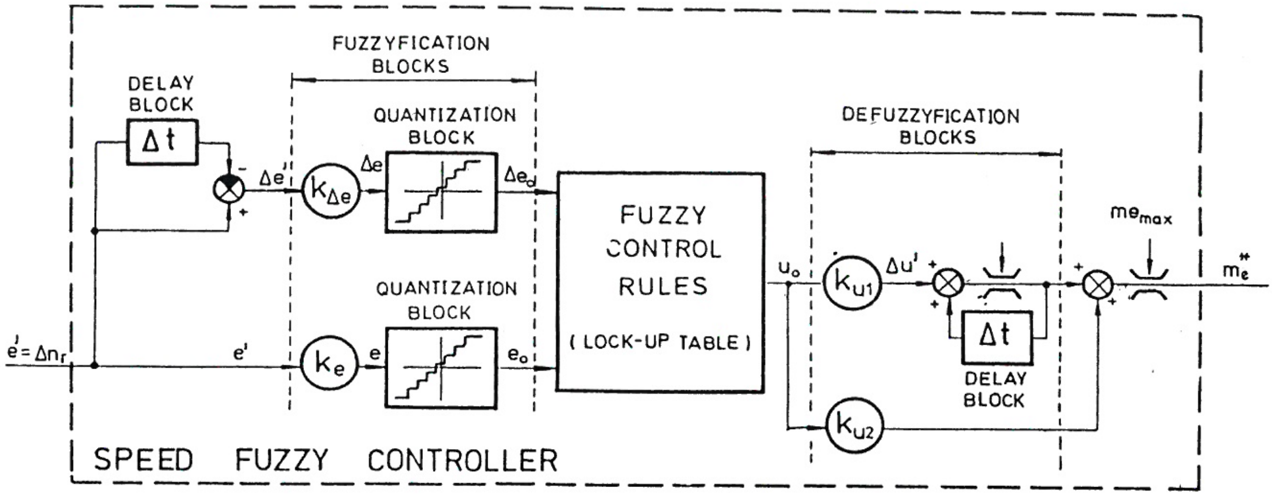

Figure 4. Block Diagram of a Fuzzy Controller.

presented in Figure 1. The flux controller is a numerical PI controller with $k_P = 5000$ and $k_I = 35.71$. The position controller is a PI one too, but its value of the integration constant ($k_I = 0.001$ and $k_P = 1$)is very small . Both controllers' structure has been chosen in the classical theory observance, and the exact parameters have been reached after completing a large number of simulations.

Speed control was exercised by a fuzzy controller. So, the input variables are the speed error Δn and the change of speed error, and the output variable is the electromagnetic torque reference m_e^* as shown in Figure 1 and Figure 4. The input variables are computed at each sampling step *k* by:

$$e'_k = \Delta n = n^*_{r_k} - n_{r_k};$$
$$\Delta e'_k = e'_k - e'_{k-1}. \quad (10)$$

The block of the **fuzzy control rules** in Figure 4 has been implemented by means of a look-up table. The fuzzy rules this paper is concerned with are based on a set of seven linguistic values presented in Table I and of which corresponding triangular fuzzy numbers are given in Figure 3.

Conforming to (9), control rules can be deduced in various ways [1]. Control rules have been designed based on experts' experiments and knowledge [2, 6] .Table II represents the look-up table with seven rows and columns, and indices within the range { -9,9} (see Figure 3) . A range of {-8,8} is also fixed for the output variable u_0.

The content of the look-up table is off-line computed and so, the demand for on-line computation made on the digital system is considerably relaxed.

Table II
The Look-up of the Fuzzy Controller

e0 \ Δe0	-9	-6	-3	0	3	6	9
-9	-8	-8	-8	-8	-6	-5	-3
-6	-8	-8	-8	-6	-4	-3	3
-3	-8	-6	-5	-3	-3	2	3
0	-6	-6	-3	0	3	6	6
3	-3	-3	2	3	5	6	8
6	-3	3	4	6	8	8	8
9	3	5	6	8	8	8	8

Hence, a very short computation time of fuzzy controllers against classical controllers.

The approximate values of the input and output scaling factors have been computed after knowing the parameters of a classical PI speed controller for the same driving system [4] . After going through many simulations, the exact values could be chosen, and they were $k_e = 2.5$, $k_{\Delta e} = 205$, $k_{u1} = 1$, $k_{u2} = 16$.

Experimental Results

On simulating the AC drive system with fuzzy controller, the authors used the ANSIM simulation program [7]. A two-phase model of the induction machine was used and the three-mono-phase PWM current converter was modelled by two-level controllers with current feedback [4].

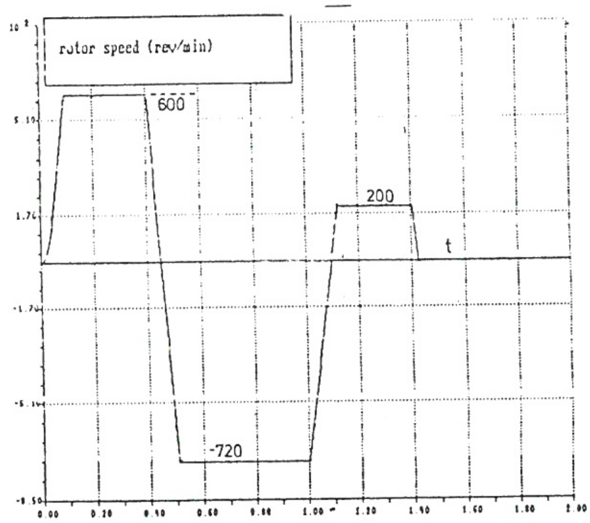

Figure 5. Speed Response of the Induction Machine by Speed and Load Commands.

The sampling time of the control system was fixed at 100 μs. A position command for a little mechanical angle (70 degrees) was simulated and two position commands for 3600 degrees (10 revolutions) were simulated, one without speed limitation and the other with speed limitation at 720 rev/min. Another simulation was made for a speed command with more speed and load torque reference changes. The obtained results, a selection of them, are compared and discussed.

Figure 5 presents the rotor speed response of the driving system, controlled by a speed fuzzy controller, by different speed and load commands. The stator current and electromagnetic torque response are presented in Figure 6. The stator phase current is also shown in Figure 6. Figure 7 presents the responses of position, speed, stator current and electromagnetic torque for a positioning process ($\theta_r^* = 3600$ mec) with speed limitation at 720 rev/min. Figure 8 presents the responses of the same variables to one and the same command but without imposing a speed limitation. In the first case one speaks of a reduced dynamic performance (the response

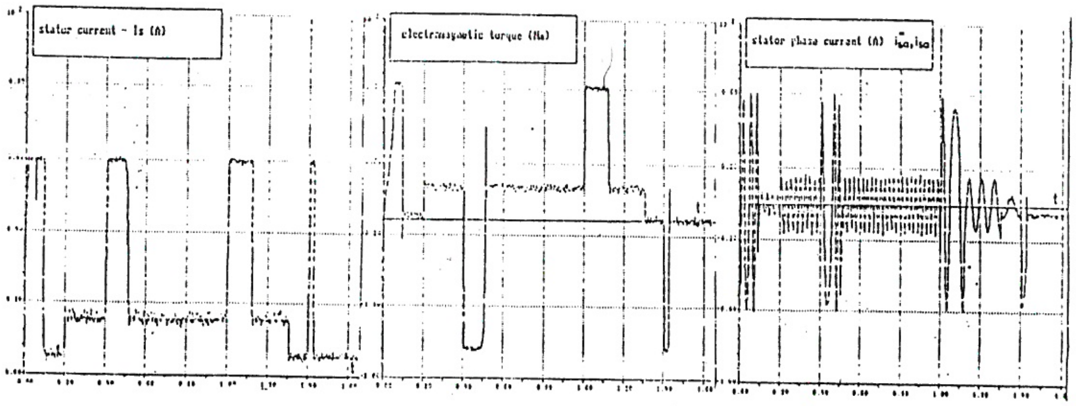

Figure 6. Stator Current, Electromagnetic Torque and Stator Phase Imposed Current Response by Speed and Load Commands

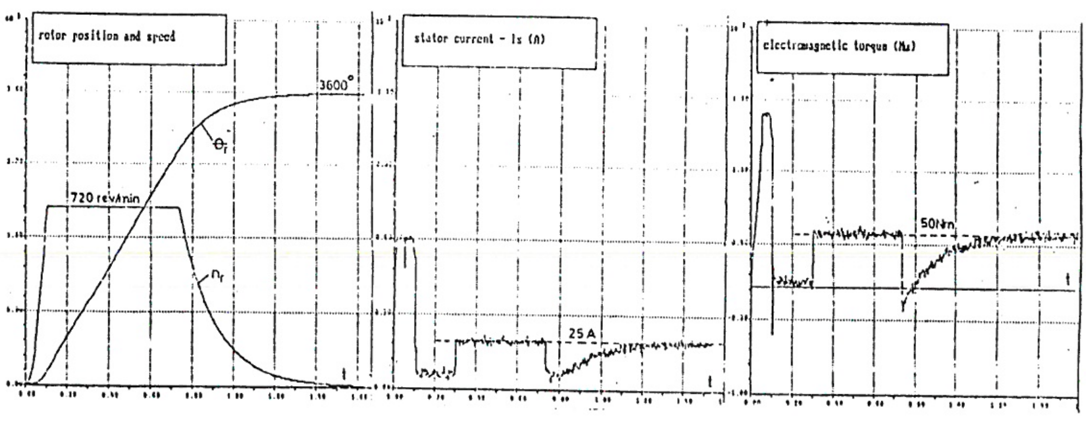

Figure 7. Position, Speed, Stator Current and Electromagnetic Torque by a Positioning Process with Fuzzy Speed Controller and Speed Limitator

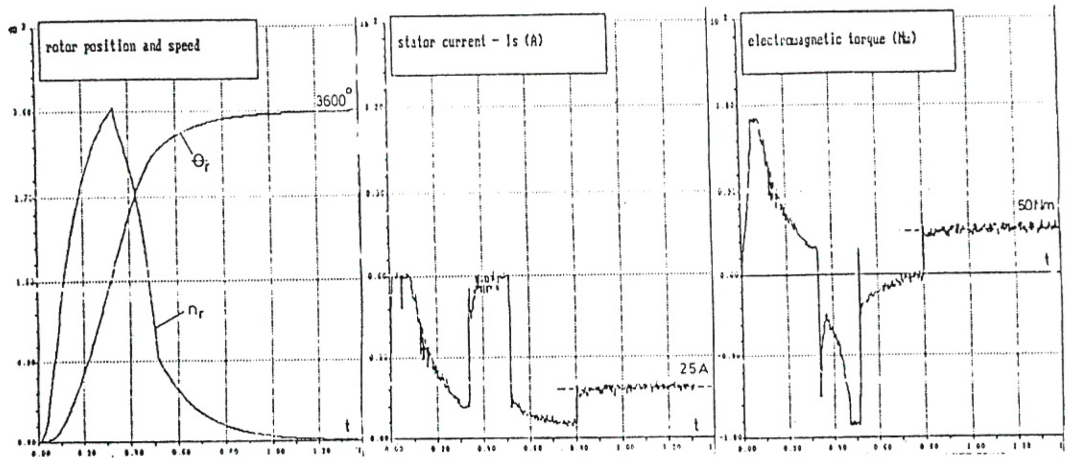

Figure 8. Position, Speed, Stator Current and Electromagnetic Torque by a Positioning Process with Fuzzy Speed Controller and without Speed Limitator.

time is $t = 1.4\ s$ for Figure 7 and $t = 1.1\ s$ for Figure 8) but of a better response of current and torgue.In either case,at different moments, a mechanical load of $m_L = 50\ N_m$ was imposed.

Conclusions

The advantages of using fuzzy controller instead of classical controllers come up with the simulation results:

- the *robustness* of control, i.e. *insensitivity to parameter variations*, is granted by the use of the same look-up table for a large number of drive configurations (different mechanical load values, different moments of inertia). Such parameter variations are characteristic to robot drives;
- very *short computing and response time*, allowing short sampling times for the drive control. It becomes possible since the contents of the look-up table is off-line computed. It ensures the use of fuzzy controllers in real-time programming;
- view of the quantization process and of the look-up table as a non-linear mapping process from e_0 and Δe_0 to u_0. This is to say that *fuzzy controller* is actually a *non-linear PI controller* and its higher performance is due to a non-linear structure.

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