An Educational Tool for Fuzzy Logic-Controlled BDCM

M. Ali Akcayol, Aydin Cetin, and Cetin Elmas, *Member, IEEE*

***Abstract*—Fuzzy logic controllers (FLC) have gained popularity in the past few decades with successful implementation in many areas, including electrical machines' drive control. Many colleges are now offering fuzzy logic courses due to successful applications of FLCs in nonlinear systems. However, teaching students a fuzzy logic controlled drive system in a laboratory, or training technical staff, is time consuming and may be an expensive task. This paper presents an educational tool for fuzzy logic controlled brushless direct current motor (BDCM), which is a part of a virtual electrical machinery laboratory project. The tool has flexible structure and graphical interface. Motor and controller parameters of the drive system can be changed easily under different operating conditions.**

***Index Terms*—Brushless direct current motor (BDCM), educational tool, fuzzy logic controller (FLC).**

I. Introduction

CLASSICAL control methods can be implemented in well-defined systems to achieve good performance of the systems. To control a system, an accurate mathematical model of the complete system must be obtained. Systems with nonlinear structure cannot be exactly modeled. The nature of fuzzy logic control has adaptive characteristics that can achieve robust response to a system with uncertainty, parameter variation, and load disturbance. Fuzzy logic, or fuzzy set theory, was first presented by Zadeh [1]. Since the introduction of fuzzy logic, many researchers have studied modeling of the complex systems, and fuzzy logic controllers (FLCs) have been broadly used to control ill-defined, nonlinear, or imprecise systems [2], [3]. In the area of the electrical machines' drive systems, fuzzy logic controllers have been applied to switched reluctance motors [4], [5], induction motors [6], brushless direct current motors (BDCM) [7], and other types of alternating current (ac) motors successfully [8]. Many colleges are now offering fuzzy logic courses as a result of successful applications of FLCs in nonlinear systems. Therefore, the quantity of the material to be taught has increased. However, this increase does not make the understanding of the course easy as the students generally tend to memorize the materials rather than to understand them. In this respect, experiments become more important to ensure that the quality of learning does not decline.

In general, experience and expertise are required for the implementation of fuzzification in complex systems which yields more time required for learning and application. The best solution for the choice of control parameters is the trial and error method, which could be accomplished in a simulation environment. Then, students may perform real experiments in a laboratory to verify theory and to interpret and discuss the results.

The presence of computers and the Internet offer many possibilities to students, researchers, and lecturers. There are many sites on the Internet related to the fuzzy logic and fuzzy controllers. There are also several software packages in the areas of fuzzy logic and neural networks, including ARISTOTLE [9], developed by Fuzzy Logic Laboratorium Linz (Hagenberg, Austria), fuzzyTECH [10], developed by Inform Software Corporation (Chicago, IL 60606 USA), O'INCA [11], developed by Intelligent Machine, Inc. (Sunnyvale, CA 94089 USA), Togai Infra Logic [12], developed by Ortech Engineering, Inc. (Webster, TX 77598 USA), and Fuzzy Logic Development Kit (FULDEK) [13], developed by Bell Helicopter Textron, Inc. (Fort Worth, TX 76101 USA). These software packages, however, are developed for limited capability and are not well suited to electrical machines.

Well-known commercial software packages such as MATLAB–Simulink, developed by Mathworks, Inc. (Natick, MA 01760–2098 USA), offer fuzzy logic toolboxes. Although students who use MATLAB–Simulink could learn the modeling process and classical and fuzzy control system designs in a sequence, only a few advanced students could achieve it in a limited time. These software solutions do not save time for learning of the fuzzy logic controlled electrical machines' drives. These solutions might be costly and time consuming for both instructors and students. Students should be able to learn the application of the fuzzy logic controlled drive system without difficulty.

In this paper, an educational tool for fuzzy logic controlled BDCM drive is presented for cost-effective education and training. The tool is a part of an electrical machinery laboratory project, which helps students learn the application of fuzzy controllers to the electrical machinery. This same tool may be used by instructors for curriculum development and teaching. The project is being developed at Gazi University, Faculty of Technical Education. The program is prepared in DELPHI environment and setup files are available.[1] The tool has flexible structure and graphical interface. Motor and controller parameters of the drive system can be changed easily under different operating conditions. In Section II, an FLC is described, and some basics of the fuzzy controller are given. In Section III, a mathematical model of a BDCM is described. In Section IV, the fuzzy logic control of BDCM is presented. In Section V, the tool is explained in detail.

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The authors are with Gazi Universitesi, Teknik Egitim Fakultesi, Elektrik Bolumu, Ankara 06500, Turkey (e-mail: celmas@tef.gazi.edu.t).
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[1]The tool can be downloaded from http://w3.gazi.edu.tr/~celmas for no cost.

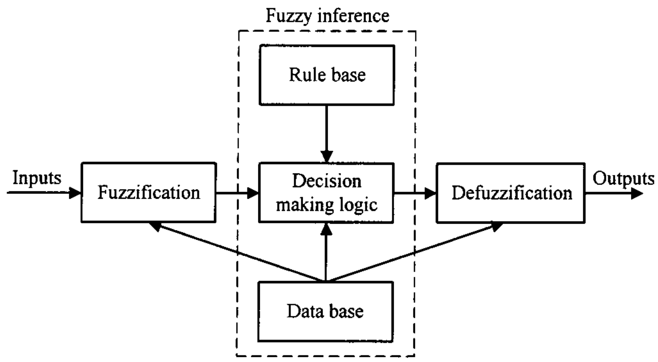

Fig. 1. Fuzzy logic controller block diagram.

II. Fuzzy Logic Controller

Fuzzy logic expresses operational laws in linguistic terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore, traditional control methods become infeasible in these systems. However, fuzzy logic's linguistic terms provide a feasible method for defining the operational characteristics of such systems.

Fuzzy logic controllers can be considered as a special class of symbolic controllers. The configuration of the fuzzy logic controller block diagram is shown in Fig. 1. The three features of symbolic controllers become *fuzzification*, *fuzzy inference*, and *defuzzification*.

A. Fuzzification

Multiple measured crisp inputs first must be mapped into fuzzy membership functions. This process is called fuzzification. The fuzzification process requires good understanding of all the variables.

Fuzzy logic's linguistic terms are most often expressed in the form of logical implications, such as *If–Then* rules. These rules define a range of values known as fuzzy membership functions. Fuzzy membership functions may be in the form of a triangle, a trapezoid, a bell (as seen in Fig. 2), or another appropriate form.

Triangle membership function is defined in (1). Triangle membership functions' limits are defined by Val1, Val2, and Val3.

$$\mu(u_i) = \begin{cases} \dfrac{u_i - \text{Val1}}{\text{Val2} - \text{Val1}}, & \text{Val1} \le u_i \le \text{Val2} \\ \dfrac{\text{Val3} - u_i}{\text{Val3} - \text{Val2}}, & \text{Val2} \le u_i \le \text{Val3} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Trapezoid membership function is defined in (2). Trapezoid membership functions' limits are defined by Val1, Val2, Val3, and Val4.

$$\mu(u_i) = \begin{cases} \dfrac{u_i - \text{Val1}}{\text{Val2} - \text{Val1}}, & \text{Val1} \le u_i \le \text{Val2} \\ 1, & \text{Val2} < u_i < \text{Val3} \\ \dfrac{\text{Val4} - u_i}{\text{Val4} - \text{Val3}}, & \text{Val3} \le u_i \le \text{Val4} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

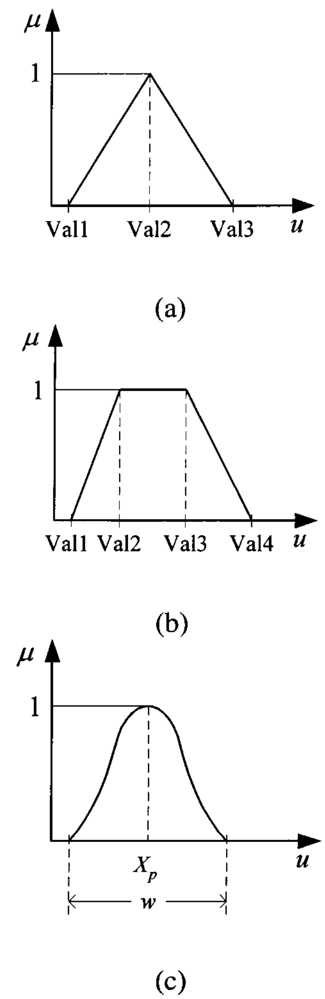

Fig. 2. (a) Triangle, (b) trapezoid, and (c) bell membership functions.

Bell membership functions are defined by parameters X_p, w, and m as follows:

$$\mu(u_i) = 1 \Bigg/ \left(1 + \left(\frac{|u_i - X_p|}{w}\right)^{2m}\right) \tag{3}$$

where Xp is the midpoint and w is the width of the bell function. $m \ge 1$, and describes the convexity of the bell function.

The inputs of the fuzzy controller are expressed in several linguistic levels. As seen in Fig. 3, these levels can be described as positive big (PB), positive medium (PM), positive small (NB), or in other levels. Each level is described by a fuzzy set.

In general, experience and expertise are required for the implementation of fuzzification in complex systems.

B. Fuzzy Inference

The second phase of the fuzzy logic controller is its fuzzy inference where the knowledge base and the decision-making logic reside. The rule base and the database form the knowledge base. The database contains descriptions of the input and output variables. The decision-making logic evaluates the control rules. The control-rule base can be developed to relate the output actions of the controller to the obtained inputs.

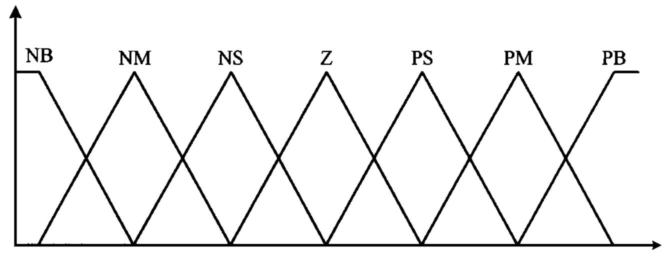

Fig. 3. Seven levels of fuzzy membership function.

C. Defuzzification

The output of the inference mechanism are fuzzy output variables. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables. This conversion is called defuzzification. One may perform this operation in several ways. One of the most common ways is the use of the height method.

In the height method, the centroid of each membership function for each rule is first evaluated. The final output, U_0, is then calculated as the average of the individual centroids, weighted by their heights as follows:

$$U_0 = \frac{\sum_{i=1}^{n} u_i \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)}. \tag{4}$$

III. Mathematical Model of the BDCM

The BDCM has three stator windings and a permanent magnet on the rotor. Rotor-induced currents can be neglected due to the high resistivity of both the magnet and the stainless steel [14]. No damper windings are modeled. In Fig. 4, the connected BDCM equivalent circuit is shown.

The circuit equations of the three windings in phase variables are obtained as follows:

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

where V_{AS}, V_{BS}, and V_{CS}, are stator phase voltages; R_a, R_b, and R_c are winding resistances; i_{as}, i_{bs}, and i_{cs} are stator phase currents; L_a, L_b, and L_c are self-inductances of phases a, b, and c; L_{ab}, L_{bc}, and L_{ac} are mutual inductances between phases a, b, and c; and e_a, e_b, and e_c are phase back electromotive forces (emfs). It has been assumed that the resistances of all the windings are equal. It also has been assumed that if there is no change in the rotor reluctance with angle, then

$$L_a = L_b = L_c = L \tag{6}$$

$$L_{ab} = L_{bc} = L_{ca} = M \tag{7}$$

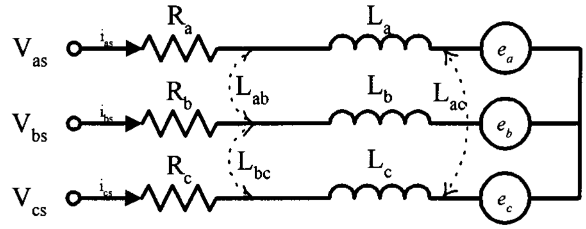

Fig. 4. BDCM equivalent circuit.

and

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{8}$$

because

$$i_a + i_b + i_c = 0 \tag{9}$$

then

$$Mi_b + Mi_c = -Mi_a. \tag{10}$$

Therefore, in state space form

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}. \tag{11}$$

It has been assumed that back emfs e_a, e_b, and e_c have sinusoidal waveform

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_r \cdot \lambda_m \begin{bmatrix} \sin(\theta_r) \\ \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \tag{12}$$

where ω_r is the angular rotor speed in radians per second, λ_m is the flux linkage, and θ_r is the rotor position in radians.

The electrical torque, in Newtons, is defined as

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_r. \tag{13}$$

The moment of inertia is described as

$$J = J_m + J_l \tag{14}$$

and the net torque is defined as

$$T = T_e - T_l. \tag{15}$$

The motion equation can be expressed as

$$T_e = J \frac{1}{P} \frac{d}{dt} \omega_r + \frac{B}{P} \omega_r + T_l \tag{16}$$

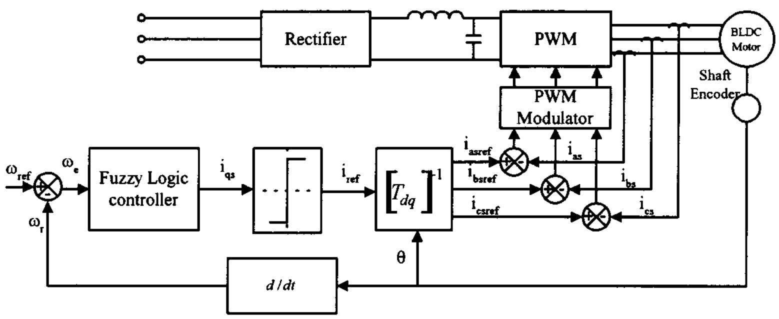

Fig. 5. Fuzzy logic speed control block diagram of the BDCM.

and the relation between rotor speed and position is

$$\omega_r = \frac{d}{dt}\theta_r. \tag{17}$$

The damping coefficient B is generally small and often neglected. Thus, the system's mathematical model in state space form is

$$\frac{d}{dt}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ \omega_r \\ \theta_r \end{bmatrix} = \begin{bmatrix} -\frac{R}{L-M} & 0 & 0 & 0 & 0 \\ 0 & -\frac{R}{L-M} & 0 & & 0 \\ 0 & 0 & -\frac{R}{L-M} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ \omega_r \\ \theta_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{P}{2.J} \end{bmatrix}\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \\ M_m \end{bmatrix} + \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}. \tag{18}$$

IV. Fuzzy Logic Control of the BDCM

The fuzzy logic controller was applied to the speed loop by replacing the classical polarization index (PI) controller. The fuzzy logic controlled BDCM drive system block diagram is shown in Fig. 5. The input variable is the speed error (ω_e), and change in the speed error (ω_{ce}) is calculated by the controller with ω_e. The output variable is the torque component of the reference current (i_{qs}) where i_{qs} is obtained at the output of the controller by using the change in the reference current (Δi_{qs}).

By applying inverse transform, reference currents for each phases i_{asref}, i_{bsref}, and i_{csref} are obtained. Transformation and inverse transformation is given in (19a) and (19b).

$$[T_p] = \frac{3}{2}\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{19a}$$

$$[T_p]^{-1} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) & 1 \end{bmatrix}. \tag{19b}$$

To apply inverse transformation, position feedback is required and is received from a shaft encoder. Hysteresis current controller forces the stator currents to be as close as the reference currents so that error approaches zero. The variables are represented in terms of per unit values. The speed error and change in the speed error is defined in the range of

$$-1 \le \omega_e \le +1 \tag{20}$$

and

$$-1 \le \omega_{ce} \le +1 \tag{21}$$

and the output variable torque reference current change (Δi_{qs}) is defined in the range of

$$-1 \le \Delta i_{qs} \le +1. \tag{22}$$

The steps for the speed control are as follows:

1) sampling of the speed signal of the BDCM;
2) calculation of the speed error and the change in speed error;
3) determination of the fuzzy sets and membership functions for the speed error and the change in speed error;
4) determination of the control action according to the fuzzy rule;
5) calculation of the Δi_{qs} by height defuzzification method;

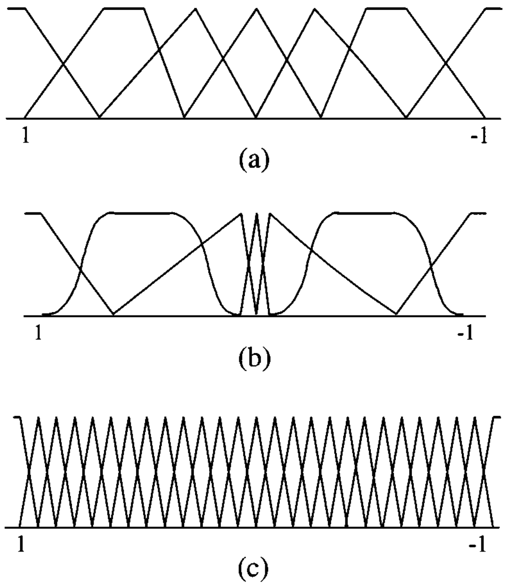

Fig. 6. Fuzzy membership functions for the (a) speed error, (b) change in the speed error, and (c) change in the torque reference current.

TABLE I
7 × 7 RULE BASE TABLE USED IN THE SYSTEM

φ_{ce} \ φ_e	NB	NM	NS	Z	PS	PM	PB
NB	0	0.1	0.2	0.3	0.4	0.6	1
NM	-0.1	0	0.1	0.2	0.3	0.4	0.6
NS	-0.2	-0.1	0	0.1	0.2	0.3	0.4
Z	-0.3	-0.2	-0.1	0	0.1	0.2	0.3
PS	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2
PM	-0.6	-0.4	-0.3	-0.2	-0.1	0	0.1
PB	-1	-0.6	-0.4	-0.3	-0.2	-0.1	0

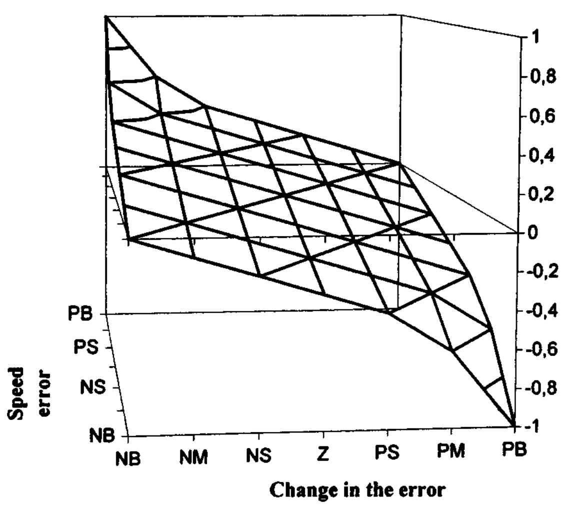

Fig. 7. Control surface.

6) sending the control command to the system after calculation of Δi_{qs}.

Fig. 6 shows the membership functions for the speed error, the change in the speed error, and the change in the torque reference current. For all variables, seven levels of fuzzy membership functions are used.

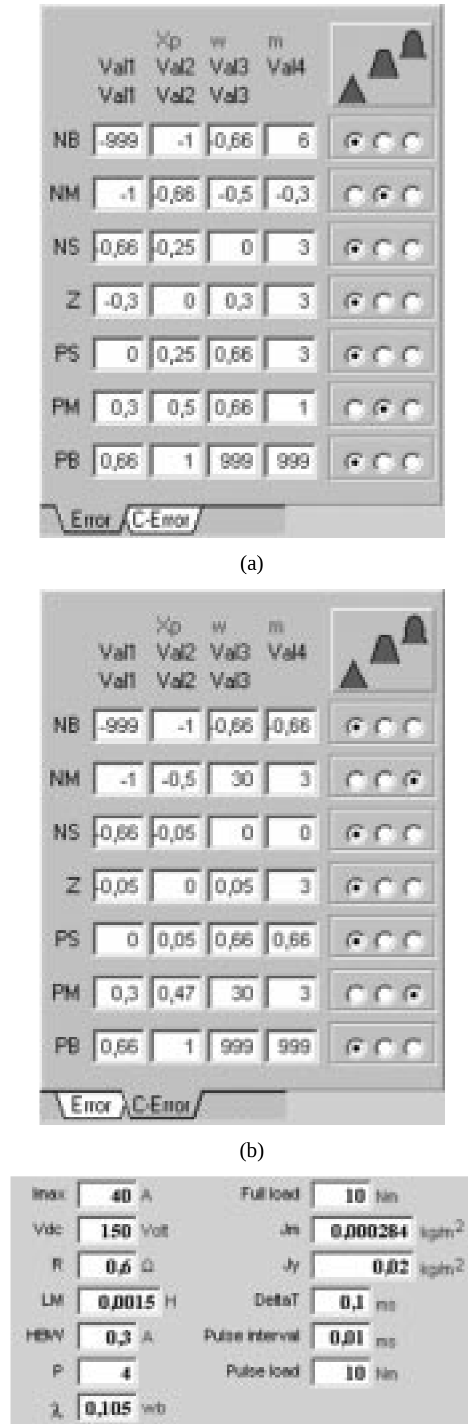

Fig. 8. Database tables for the (a) error, (b) change in the error, and (c) motor.

Table I shows the 7 × 7 rule base table that was used in the system. Fig. 7 shows the control surface for the controller, and Fig. 8 shows the database values. Database values contain data for error, the change in the error, and the motor parameters.

V. THE EDUCATIONAL TOOL

A. Main Window

The tool works in a Windows environment. The drive system operation can be observed on a PC monitor and can be modified

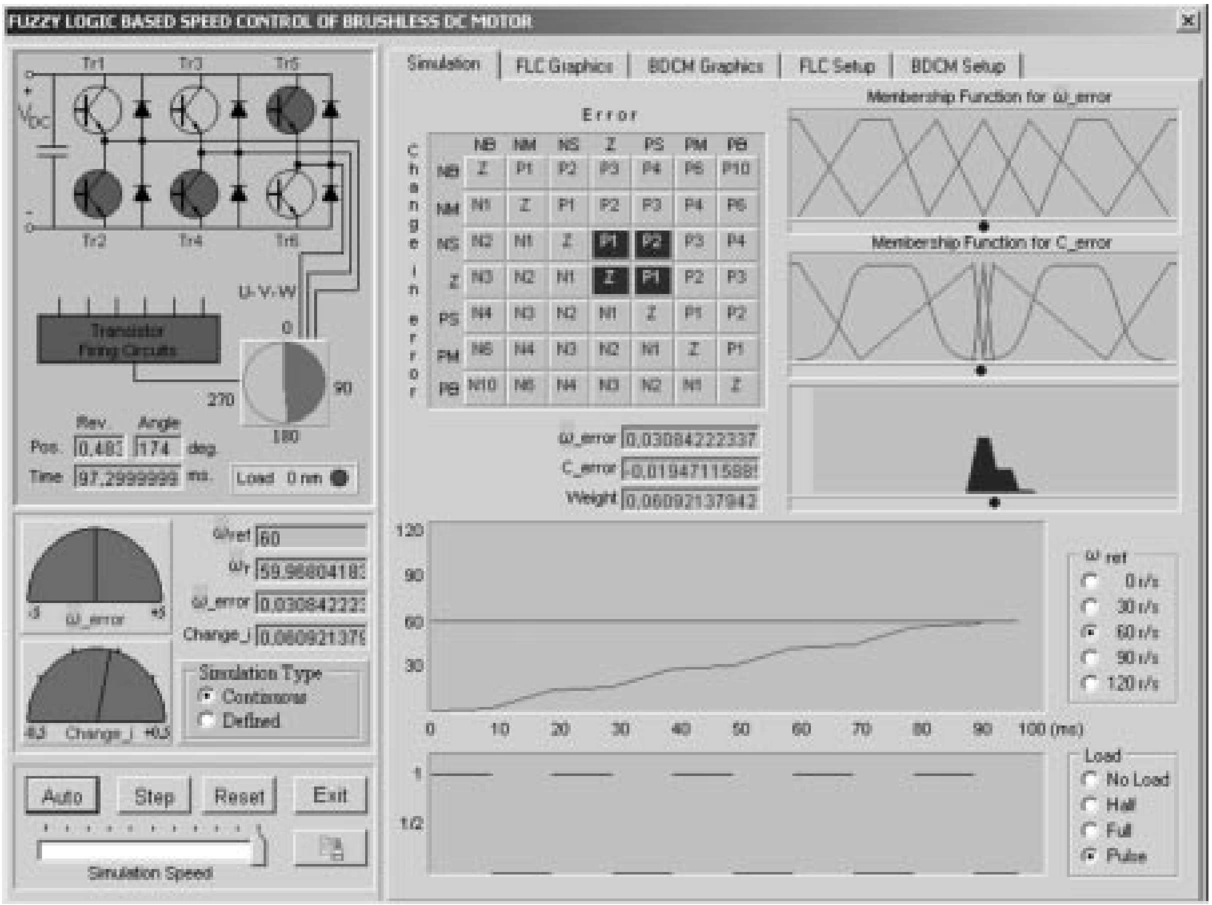

Fig. 9. The main window.

by choosing appropriate windows. A control window and another selected window can be seen simultaneously by pressing desired button on the top of the screen. A view of the main program window is shown in Fig. 9. The main window is divided into two sections, namely, the control window, which is on the left, and the menu window on the right. The contents of the control window do not change when the program is running. In the control window, operation of the entire system [i.e., the working of voltage source inverter, transistor switches operation, position of the rotor, reference and actual speed values, speed error, and change in the error (both can be seen analytically and graphically)] can be observed. By using the buttons at the bottom, the user may control the simulation process.

The menu window has five subwindows, and the contents of the menu window changes according to the chosen window from the menu. When one of the windows is chosen, the chosen window replaces the previous menu window. These windows are shown in Figs. 10–14. Although a student may start the tool directly by using default values of the program given for a specific BDCM and a fuzzy logic controller, to start a new simulation, parameters related to the motor, fuzzy controller, and simulation should be entered by the user. The user must select BDCM setup, FLC setup, and simulation windows. Once the simulation has been started, the user may select any window to see how the system is working.

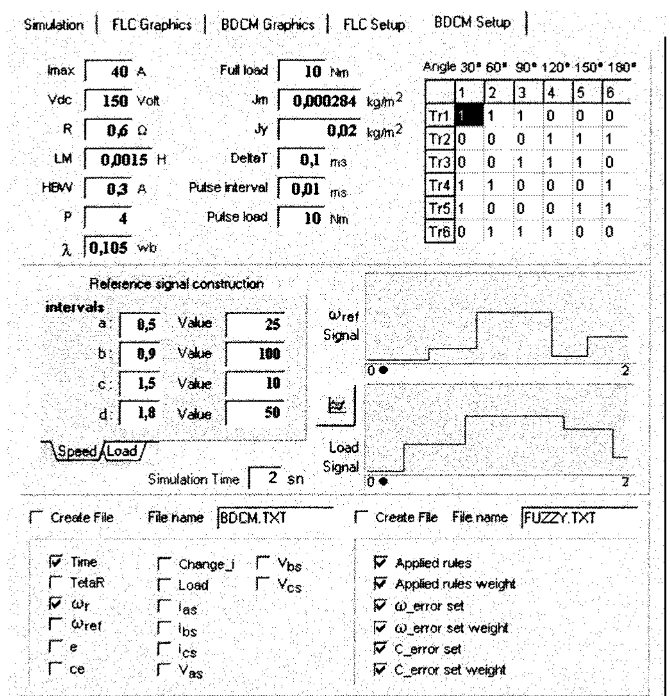

Fig. 10. BDCM setup window.

BDCM and FLC setup windows enable users to define motor and fuzzy logic controller parameters. At the beginning of the simulation, both BDCM and FLC setup windows are used to define parameters used in simulation.

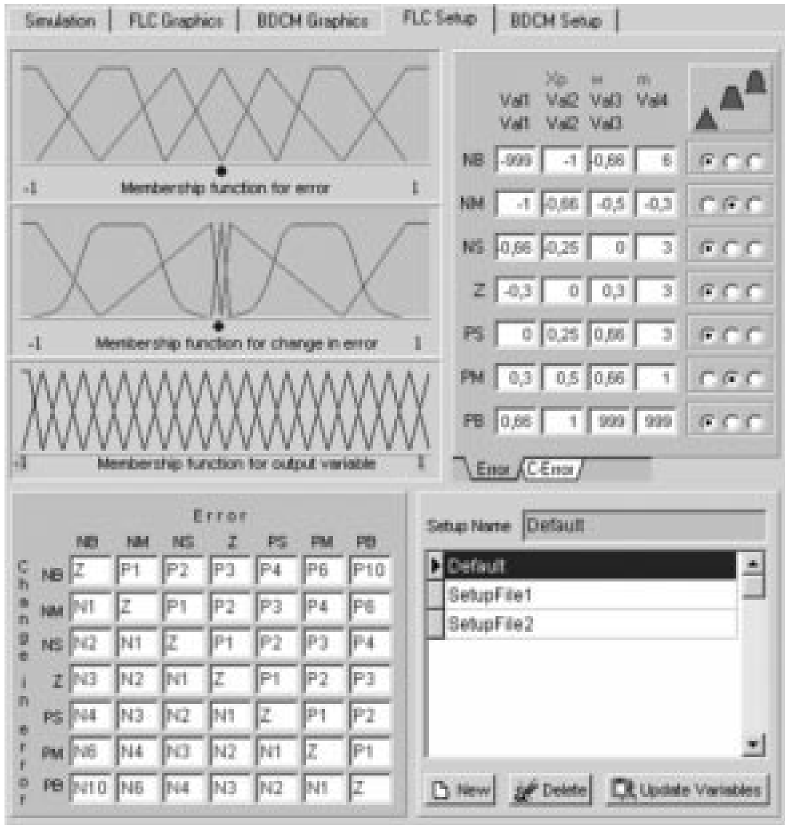

Fig. 11. FLC setup window.

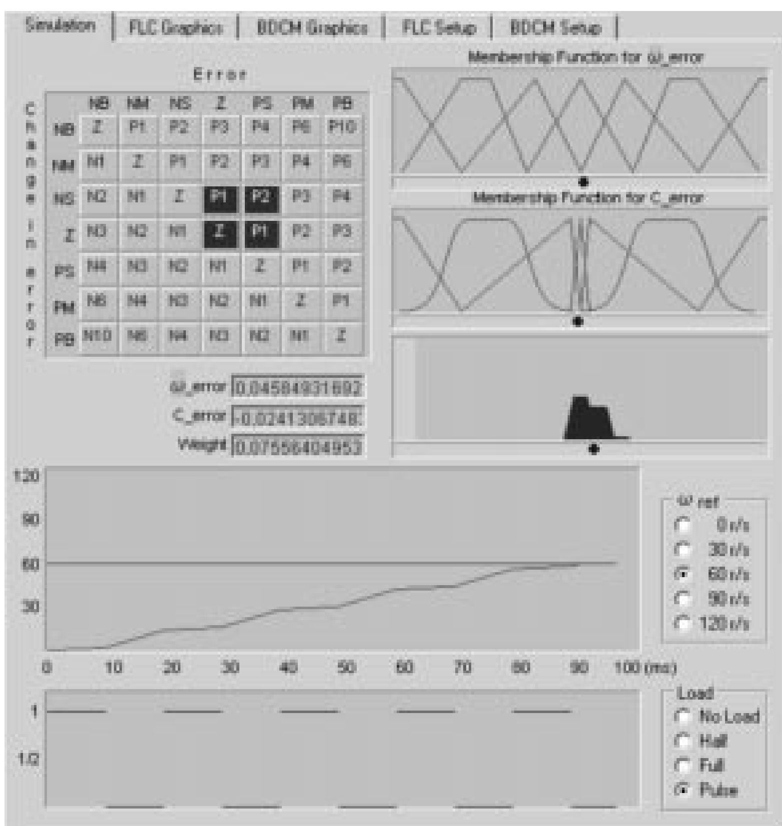

Fig. 12. Simulation window.

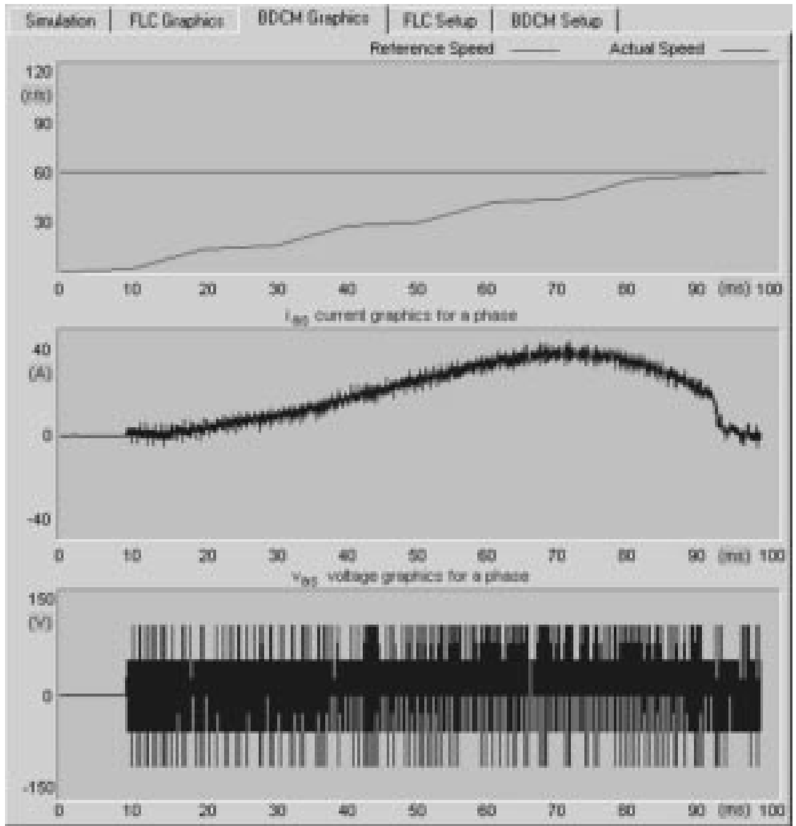

Fig. 13. BDCM graphics window.

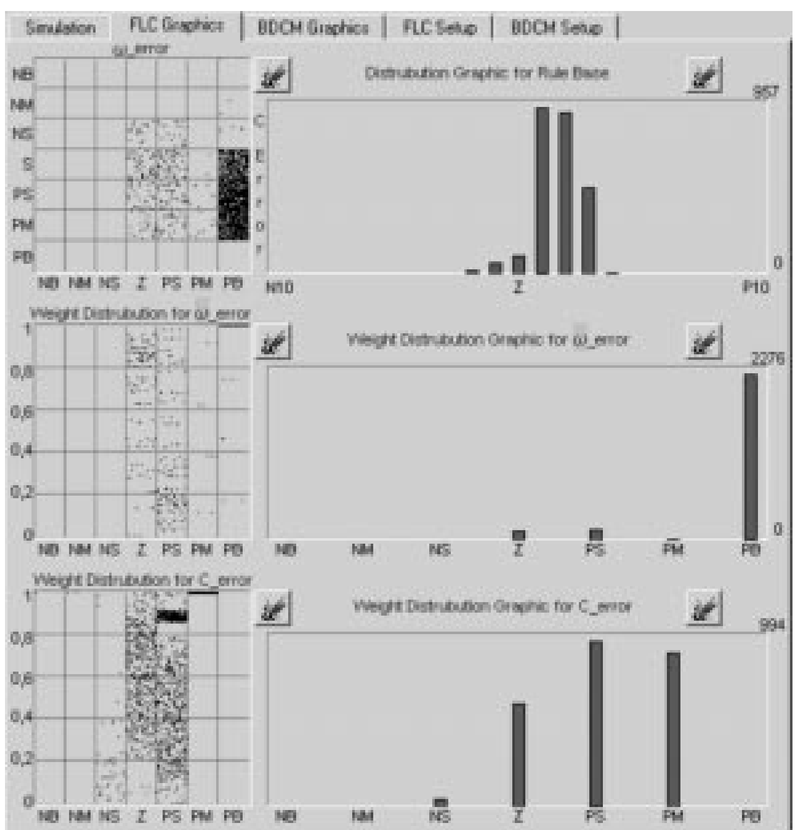

Fig. 14. FLC graphics window.

B. BDCM Setup Window

In the BDCM setup window (Fig. 10), motor and load parameters are defined according to the simulation type. For example, a motor can be simulated according to the chosen load type, i.e., pulse, no load, half load, or full load conditions. Moreover, a user may define a load function and speed function between specified time intervals during the simulation time. Simulation parameters and data can be saved in a user defined text file by selecting check boxes. Moreover, the user can save simulation data with a file extension *.dat* or *.mat*. This procedure enables a person to use any DOS- or Windows-based editor (i.e., Excel, Word), or a specific program, such as MATLAB, to view and plot simulation results.

C. FLC Setup Window

In the FLC setup window (Fig. 11), fuzzy controller parameters are defined. Because fuzzy logic control depends on user experience, a flexible rule base can be defined. Three types of membership functions are given in the program for the error and the change in the error. These are triangle, trapezoid, and bell functions. Each membership function can be defined by the user. Triangle membership functions' limits are defined by Val1, Val2, and Val3. Trapezoid membership functions' limits are defined by Val1, Val2, Val3, and Val4. Bell membership functions are defined by parameters X_p, w, and m.

By selecting the appropriate circle each function's values can be set or altered. Membership function for error and for change in the error may be composed of only one function, or either two functions, or three membership functions, i.e., triangle, trapezoid, or bell function. Fuzzy control rules for the output are also defined as table in the window. The table values are stored in a database file. In the program, there are three files, named Default, SetupFile1, and SetupFile2. The user may configure these files and save in another file name or create a new file.

D. Simulation Window

The simulation window (Fig. 12) shows fuzzy control rules for the output created in the FLC setup window and other graphics which are speed, load, membership function for the error, membership function for the change in the error, and the defuzzification process according to the height method.

During the simulation, speed error and the change in the error and weight can be observed. Also, reference speed and load can be changed by selecting the appropriate circle.

E. BDCM Graphics Window

BDCM graphics window (Fig. 13) shows speed, current, and voltage graphics of the BDCM. Reference speed and actual speed of the motor are plotted in different colors in the graphics window.

F. FLC Graphics Window

In the FLC graphics window (Fig. 14), distribution graphics for the rule base, weight distribution for the speed error, and weight distribution for the change in the error are given. In addition, on the left of the window, used rules density in the rule base table, weight distribution density for the speed error, and weight distribution density for the change in the error are given. The eraser symbol is used to clear graphics in the window.

VI. Conclusion

In this paper, an educational tool for fuzzy logic controlled BDCM drive is presented for cost-effective education and training. The tool helps students to improve their trough understanding on both FLC and BDCM. It is intended as an aid to teaching and may be used by instructors for curriculum development. The tool can be installed on a PC operating in a Windows environment (Windows 95, 98, ME, or NT) and freeware. The tool has flexible structure and graphical interface and enables users to change controller and motor parameters easily under different operating conditions.

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M. Ali Akcayol received the B.S. and M.S. degrees in electronics and computer education from Gazi University, Faculty of Technical Education, Ankara, Turkey, in 1993 and 1998, respectively. He is currently pursuing the Ph.D. degree at Gazi University.

His research interests include intelligent control, fuzzy logic control and neural networks.

Aydin Cetin received the B.S. degree in electrical and electronics education from Gazi University, Faculty of Technical Education, Ankara, Turkey, in 1987 and the M.Sc. degree in electrical engineering from Louisiana State University, Baton Rouge, in 1996. He is currently pursuing the Ph.D. degree in electrical education at Gazi University, Institute of Science and Technology, Ankara, Turkey.

From 1989 to 1993, he worked as a research assistant at Gazi University, Faculty of Technical Education. He completed the teacher-training course in electrical engineering at Purdue University School of Technology, West Lafayette, IN, in 1990. He is currently teaching at Gazi University, the Institute of Science and Technology. His research interests include power quality, power electronics, electrical machines and drives, intelligent control, digital signal processing, and web-based distance learning.

Mr. Cetin received a scholarship from the Turkish Higher Educational Counsel for his Master's work in 1993.

Cetin Elmas (S'91–M'93) received the B.S. degree in electrical and electronics education and the M.Sc. degree in electrical education from Gazi University, Ankara, Turkey, in 1986 and 1989, respectively, and the Ph.D. degree in electronic and electrical engineering from the University of Birmingham, Birmingham, U.K., in 1993.

From 1987 to 1989, he was a Research Assistant with Gazi University, Faculty of Technical Education. From 1994 to 1995, he was an Assistant Professor at Gazi University, and he was an Associate Professor from 1995 to 2001. He is currently a Full Professor and the head of the Department of Electrical Machinery. His research interests include power electronics, electrical machines and drives, intelligent control, digital signal processing, and engineering technology education.