

# Virtual Electrical Machinery Laboratory: A Fuzzy Logic Controller for Induction Motor Drives\*

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*In this paper, an educational tool was presented to supplement existing undergraduate and graduate electrical machinery laboratory instruction, so that students could establish a thorough understanding of a fuzzy logic controller (FLC) and an indirect vector control induction motor (IM) drive using the FLC. The tool describes the basic operation of the indirect vector controlled IM drive and, application of fuzzy logic speed control to the vector controlled IM. The FLC was applied to the speed loop, replacing the conventional PI controllers. The educational tool allowed the student to interact with the indirect vector controlled IM drive using the FLC and to examine its responses on a dynamic and instantaneous basis under different operating conditions.*

## INTRODUCTION

IN ENGINEERING courses today, there is a growing movement to integrate into the curriculum several aspects of the real world including design, teamwork and communication skills. Traditionally, classroom and laboratory have been used to teach these courses. A common difficulty in the explanation and analysis of real world problems is how to describe inside the systems. Either the instructor provides a description that is almost word-by-word as shown in a textbook table or the students gain widely varying perceptions as to what the situation is. In either case, students are unable to demonstrate engineering judgment.

With the development of technology and the computer in particular, the virtual classroom or virtual laboratory, which is the computer-related definition of that created through the imagination, becomes a possible option for teaching and learning.

The electrical machinery course curriculum is also being updated with the advance of technology. Induction motors and their control are being covered in revised course curricula, causing an increase in the quantity of the material to be taught. However, the increase in quantity does not increase the understanding of the course. The presence of PCs offers many possibilities to students, researchers, and lecturers at college, and even at home and also distance-learning at another university [1].

There are many sites in 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 (i.e. ARISTOTLE, Fuzzy-TECH, FULDEK and MATLAB/Fuzzy Logic

Toolbox). These software packages, however, have limited capability and are not well suited to electrical machines. Although students who use MATLAB/Simulink could learn the modeling process, only a few advanced students could master it in a limited time.

This paper presents a PC-based educational tool to supplement existing undergraduate and graduate laboratory instruction and to provide students a thorough understanding of both fuzzy logic controllers (FLC) and indirect vector controlled IM drives with the FLC under different loads and speed. The tool is a part of the virtual electrical machinery laboratory project which covers DC and AC machines. These educational tools has been developed by the authors at Gazi University Faculty of Technical Education, Ankara, Turkey. The tool was prepared in DELPHI and works in Windows environment (Windows 95, 98, ME, 2000, NT or XP). The tool may be used by anyone, who is interested in FLC, the IM and FLC-controlled IM, in a laboratory or at home. The tool is available from the authors for no cost by sending an e-mail to the corresponding author.

## VECTOR CONTROL OF INDUCTION MOTOR DRIVE WITH FUZZY LOGIC CONTROLLER

A high performance control technique such as indirect field-oriented control, which is also known as vector control, is used widely for induction motor drives in industrial applications. The aim of field-orientation is to control an AC machine to obtain the performance characteristics similar to a separately excited DC machine. In fact, with vector control, induction motor drive outperforms the DC drive because of higher transient current

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capability, increased speed range and lower rotor inertia, providing good efficiency and excellent dynamic performance [2].

In vector control, the input stator current of squirrel-cage induction motors is controlled so that it is decoupled into flux and torque producing components. Thus, the IM can have a control structure as in a DC motor. This control method requires knowledge of the instantaneous position of the rotor flux to achieve the decoupling and calculates the rotor flux position angle from the slip and rotor speed. The IM is one of the motors attractive to researchers in variable speed applications due to advantages over other motor drives [3].

Vector control is the foundation of modern high performance drives. Vector control techniques can be classified as indirect or feed forward method and direct or feedback method depending on the method of unit vector generation for vector transformation. There is also classification of control based on orientation with rotor flux  $\lambda_r$  or stator flux  $\lambda_s$ .

The synchronously rotating vector components of stator current  $i_{qs}$  and  $i_{ds}$  are controlled independently to control the torque and rotor flux, respectively. The drive can easily be operated from zero speed to the constant power field-weakening region.

The conventional control design is based on a mathematical model that may often be unknown, ill-defined, nonlinear, complex and multivariable with parameter variation. As an intelligent control technology the FLC has the potential to accommodate an improved method of determining nonlinear models which are complementary to conventional techniques [4]. The fuzzy algorithm is based on intuition and experience and can be regarded as a set of heuristic decision rules. The fuzzy algorithms have the common feature of not requiring a detailed mathematical model [5]. The FLC can give robust adaptive response to a drive

with nonlinearity, parameter variations and load disturbance effects.

The FLC provides a systematic method to incorporate human experience and applied nonlinear algorithms, characterized by a series of linguistic statements, into the controller. The FLC is gaining increasing emphasis in process control applications. Since the introduction of fuzzy set theory in 1965 by Zadeh [6], the FLC has been implemented successfully in several applications. Recent literature has explored the potentials of the FLC for machine drive applications [7–11].

The FLC was applied to the speed loop by replacing the classical PI controller in this study. The configuration of the FLC for indirect vector controlled IM drive is shown in Fig. 1. The FLC is composed of three blocks of the FLC namely, fuzzification, fuzzy inference and defuzzification.

From the energy conservation law and with the assumption of magnetic linearity, the mechanical equation of the machine is given by:

$$J \frac{d\omega}{dt} = -B\omega + T - T_L \quad (1)$$

$$\frac{d\theta}{dt} = \omega \quad (2)$$

where  $\omega$  is the speed,  $T$  is the electromagnetic torque,  $T_L$  is the load torque,  $K_t$  is the torque constant,  $J$  is the combined inertia of the rotor plus the mechanical load and  $B$  is the friction coefficient.

The FLC accepts speed error  $\omega_e$  and change in speed error  $\omega_{ce}$  as input variables. The output variable is change in the reference current ( $\Delta i_{qs}$ ). The speed error  $\omega_e$  and change in speed error  $\omega_{ce}$  are defined as:

$$\omega_e = \omega^* - \omega \quad (3)$$

$$\omega_{ce} = \omega_e - \omega_{e0} \quad (4)$$

where  $\omega^*$  is the reference speed,  $\omega$  is the actual

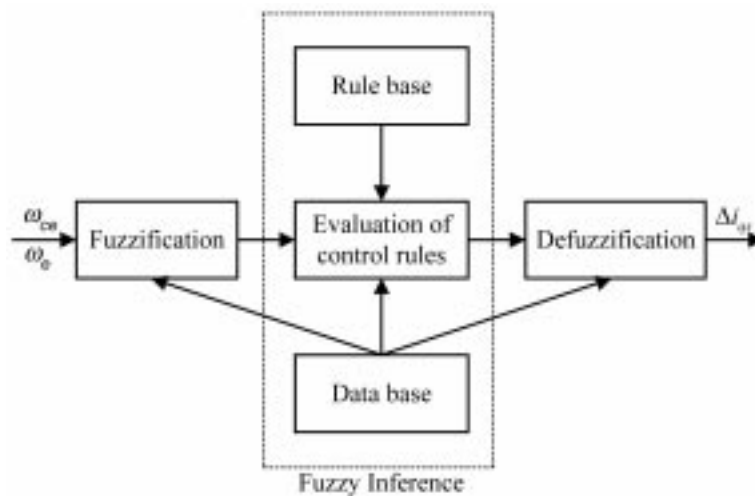


Fig. 1. The configuration of the FLC for indirect vector controlled IM drive.

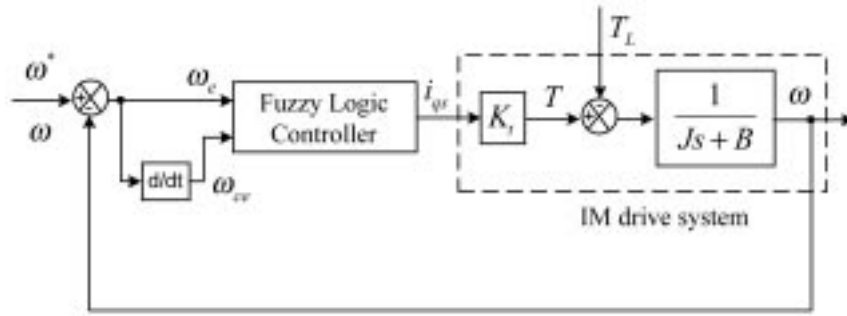


Fig. 2. The block diagram of indirect vector controlled IM drive with the FLC.

speed,  $\omega_{e0}$  is the previous speed error. The block diagram with rotor flux orientation as shown in Fig. 2 represents an application of indirect vector controlled IM drive with the FLC. As seen from Fig. 2 the FLC is applied to the speed loop of the IM.

Figure 3 shows the membership functions of the variables for FLC which are expressed in several linguistic levels. Each level is described by a fuzzy set. The levels of the inputs of the FLC were described as positive big (PB), positive medium (PM), positive small (PS), zero (Z), negative small (NS), negative medium (NM), negative big (NB). A rule matrix relates  $\omega_e$ ,  $\omega_{ce}$ , and  $\Delta i_{qs}$  variables. The input signals  $\omega_e$  and  $\omega_{ce}$  fuzzified, the corresponding control rules are evaluated from the

membership functions and rule table, composed (or combined), and finally defuzzified to derive the  $\Delta i_{qs}$ .

The steps for speed control are summarized as follows:

1. Sampling of the speed of the IM.
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 change of the control action  $\Delta i_{qs}$  according to individual fuzzy rule.
5. Calculation of the actual change of  $i_{qs}$  by centroid defuzzification method.

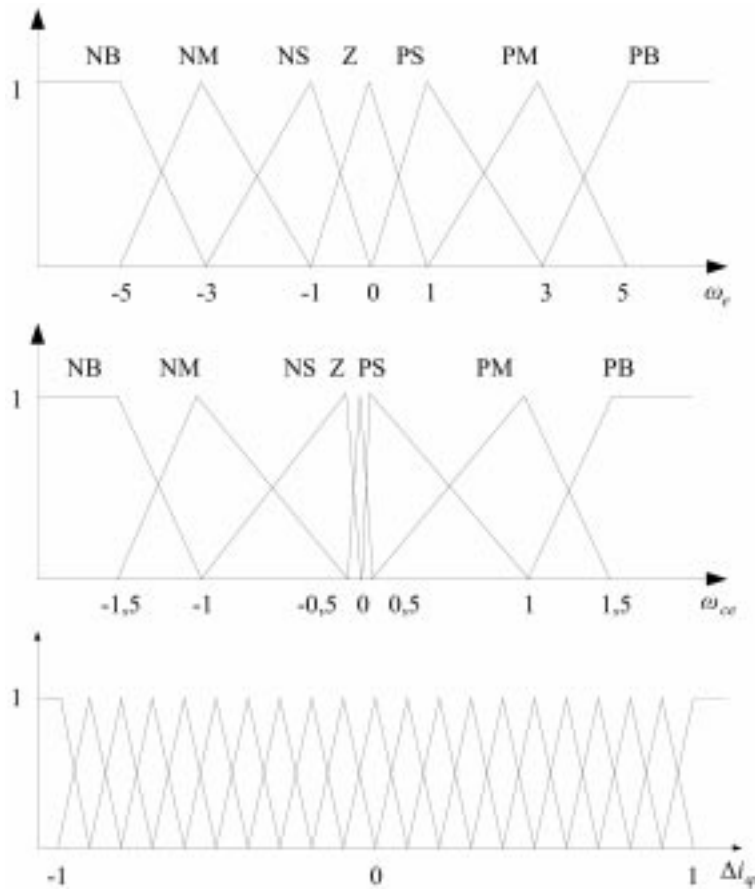


Fig. 3. Membership functions for FLC.

- Sending the change of control action  $\Delta i_{qs}$  to control the drive.

### THE OPERATIONAL PROCEDURE OF THE EDUCATIONAL TOOL

The main window of the tool has divided into two sections, namely navigation window, which is on the left and menu window on the right as shown in Fig. 4. The contents of the navigation window do not change when the program is running. In the navigation window operation of the whole system can be observed. Students can also observe on the navigation window the reference and actual speed values, speed error and change in the error analytically or graphically.

One advantage of the tool was that it could be customized to describe the performance of different types of motors. To demonstrate this with an actual test would require multiple test cells or the ability to change motors during the laboratory exercise.

The tool first required a user input to specify the motor variables and rule and membership functions of the FLC. The student may start the simulation directly by using default values of the program given for a specific IM and FLC. If the student wants to use different IM and FLC parameters for the simulation, new parameters should be entered by selecting the IM setup, FLC setup and simulation windows. Once the simulation has been started, students may select any window to see how the system is working.

The bottom right window of the tool allows the adjustment of reference speed and load. An additional menu, which is at the top, is provided to access the IM, the FLC, simulation variables, graphical functions of the tool, and to exit or change motor operating conditions.

In the IM setup window, motor and load parameters are defined as shown in Fig. 5. Figure 6 shows the FLC setup window in which FLC parameters are defined. As seen from Fig. 7 the IM graphics window shows speed, current and voltage of the IM. Figure 8 shows the FLC graphics window which indicates the distribution graphics for rule base; weight distribution for the speed error and weight distribution for the change in the error are given. Simulation window shows fuzzy logic control rules for the output created in 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 which uses the height method. 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 EVALUATION OF THE EDUCATIONAL TOOL

The induction motors and their control are an integral part of an electrical machinery laboratory exercises in the revised course curricula of electrical engineering departments at universities and technical colleges.

Traditional laboratory exercises require groups of students to carry out an electrical machine test in which they adjust motor speed and load, remote from the test rig, and they record performance data. The facilities required to perform such a test include the motor itself, a dynamometer to control the load on the motor and suitable instrumentation for measuring the desired variables. The data would at least include voltage, current, speed, and torque. One problem that is encountered with

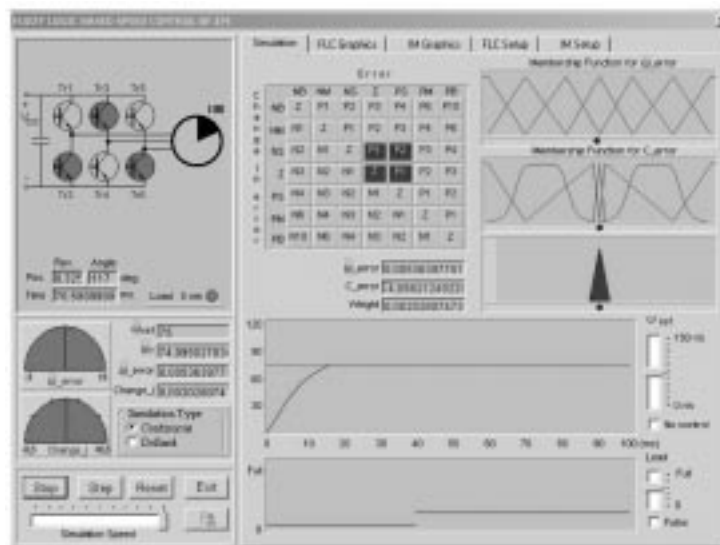


Fig. 4. The main window: navigator on the left and menu on the right.

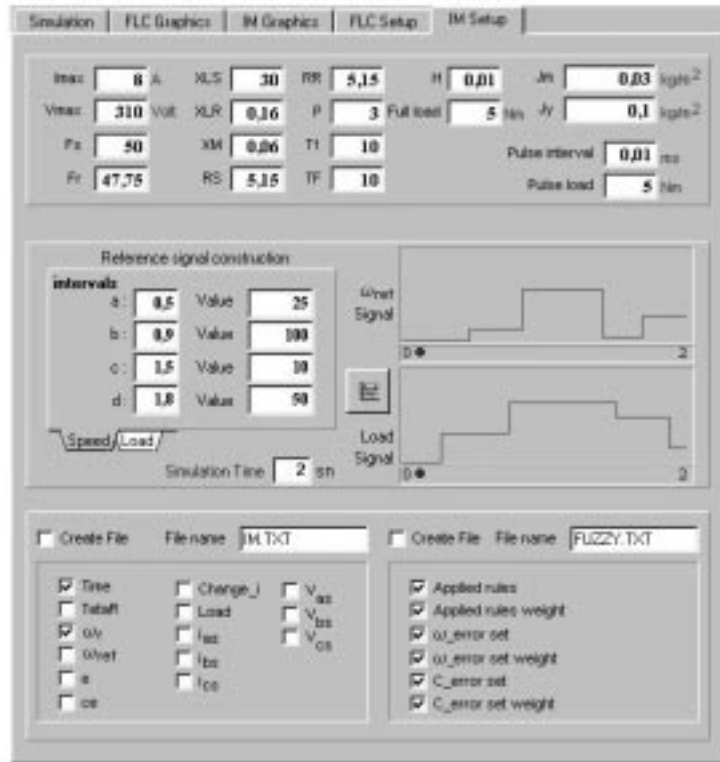


Fig. 5. IM setup window.

such laboratory exercises is that individual students are unable to perform a test because of limited time and resources. Generally, the laboratory assignments only require 3 or 4 students to make all of the required measurements and

adjustments. For larger groups of students, some may feel left out of the experience. Furthermore, if the motor is tested under limited conditions, the motor performance over its working range is not adequately demonstrated.

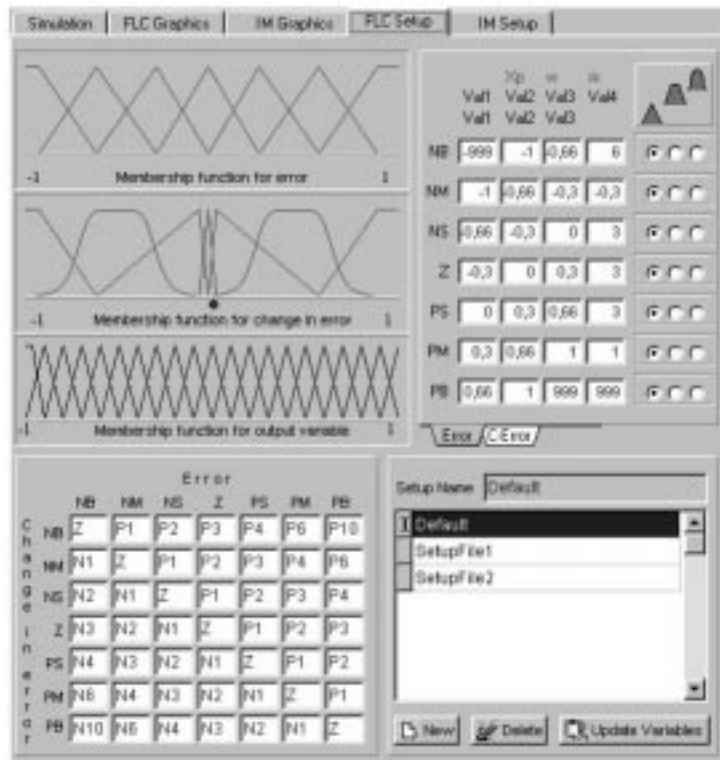


Fig. 6. FLC setup window.

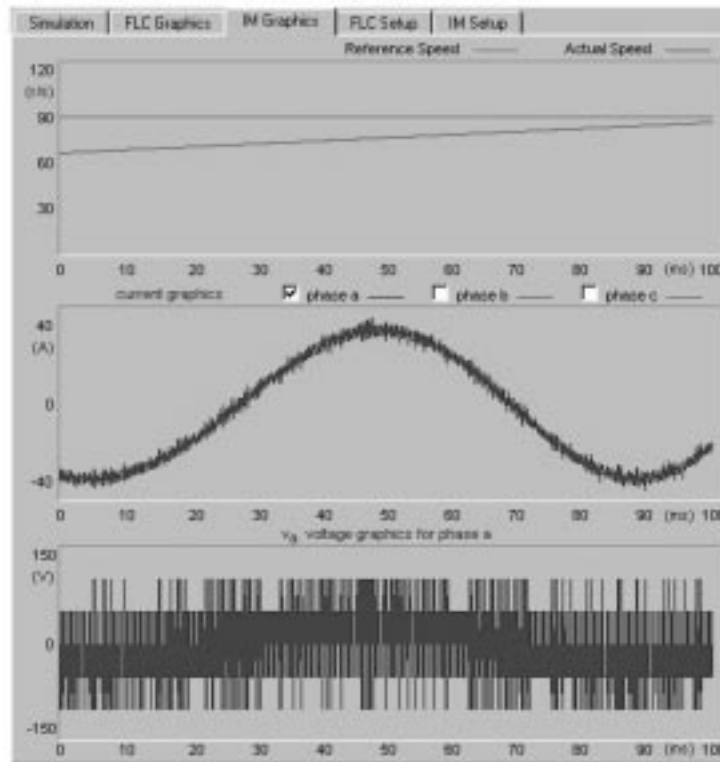


Fig. 7. IM graphics window.

The first exposure of the tool to student usage was in a fourth-year electrical machine course of 25 students, in which one of the modules taught focused on induction motors. One of the laboratory assignments is an actual induction motor with

FLC. Before studying with the tool, the students are required to attend four two-hour theoretical sessions, one involved the IM and the other sessions were about fuzzy logic. In the final session, only a one-hour lecture is allocated for

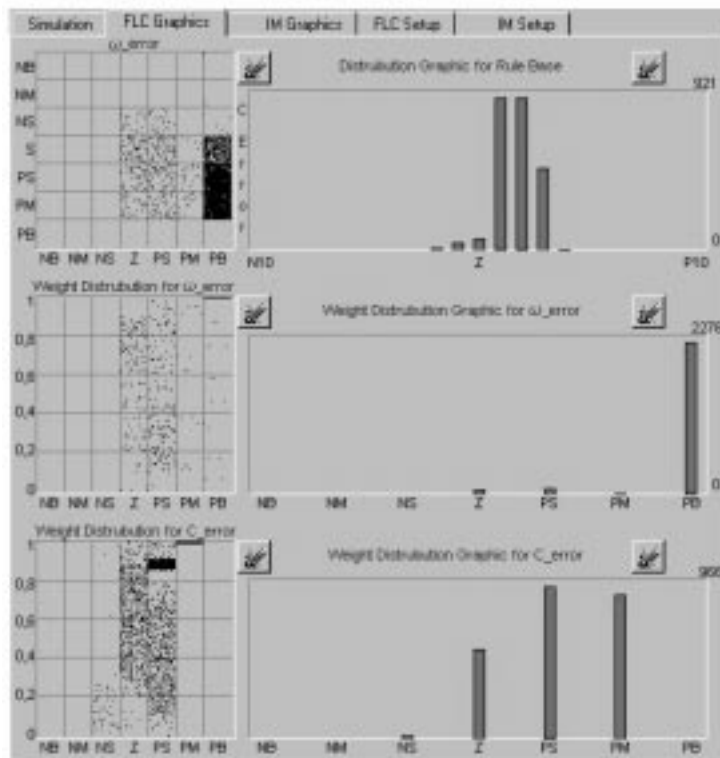


Fig. 8. FLC graphics window.

Table 1. Evaluation sheets

No	Question	Plenty/ Very well	Sufficient/ Well	Some	A little
1	How much prior knowledge of the IM did you have before attending this lab session?	4	21	0	0
2	How much prior knowledge of the IM driver did you have before attending this lab session?	1	20	4	0
3	How much prior knowledge of the vector control did you have before attending this lab session?	0	19	6	0
4	How much prior knowledge of the FLC did you have before attending this lab session?	0	20	5	0
5	Did you understand the mathematical model of the IM before attending this lab session?	1	23	1	0
6	Did the tool stimulate you to work with the lab session?	1	22	2	0
7	How much experience did you have before attending this lab session?	0	4	5	16
8	Did the experiments of the lab session with the tool fit previous knowledge?	4	21	0	0
9	Is the tool easy to use and user friendly?	21	4	0	0
10	How much do you feel you have benefited from the tool?	14	11	0	0
11	How real does the IM's dynamic characteristics obtain by the tool seem to you?	11	13	1	0
12	How do you judge your own work with the tool at this time?	10	12	3	0
13	Does this lab session with tool build on thing you have learned in theoretical session?	13	12	0	0

the description of the tool. In the first two hours, there are lectures on the motor's construction, operation principle, modeling of the motor, the drivers and vector control. In the fuzzy session, students are lectured about fuzzy sets theory and modeling.

After lectures on fuzzy logic, the students perform a series of tests with the educational tool and present the results in a report with one week deadline. The students are asked to obtain FLC for indirect vector controlled IM drive system and report the results. The educational tool undertaken is similar to what was prescribed for the IM test. Hence, it was intended that the tool assignment would provide reinforcement of what was expected for the actual test as well as give each student the opportunity to spend time with the tool and obtain a thorough understanding of the responses of the IM under different speeds and loads. Afterwards, results obtained by the use of the tool and the results obtained without using the tool are compared.

This tool has been successfully used by many students. Student response to the use of the tool is obtained through evaluation sheets as shown in Table 1. From answers to the questions, it is found that the majority of the students felt that the tool was straightforward and beneficial and had further aroused their interests.

The scores for the laboratory assignments are also higher than previous years and the understanding of this material seems to be more uniform across the class as a whole. The feedback from the introduction of the educational tool is very positive. The scores for the laboratory assignments are higher than previous years and the understanding of this material seems to be more uniform across the class as a whole.

## CONCLUSIONS

In this paper, an educational tool is presented as a virtual electrical machinery laboratory to supplement existing undergraduate and graduate electrical machinery laboratory instruction, so that students can establish a thorough understanding of both FLC and indirect vector controlled IM drive with the FLC. The tool may be used by anyone, who is interested in FLC, the IM and FLC controlled IM, in a laboratory or at home. The educational tool allows the student to interact directly with the fuzzy logic controlled IM and to examine its responses on a dynamic and instantaneous basis under different operating conditions. The educational tool as a teaching aid is very successful according to feedback from students and instructors.

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