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Full Length Research Paper

A virtual laboratory for fuzzy logic controlled DC motors

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Direct current (DC) motors have currently a wide usage in industrial applications. This resulted in the necessity of making the speed controls of DC motors in a sensitive manner. Conventional controllers have poorer performances due to the non-linear features of DC motors like saturation and friction. Fuzzy logic controllers (FLC) are widely used in controlling poorly-defined, nonlinear and imprecise systems. FLC courses are being given in many universities at the graduate and/or postgraduate levels due to FLC achievements in these areas. The education of a FLC driver in a lab environment is a time-consuming and expensive task. In this study, a virtual lab is prepared for the FLC of a permanent magnet direct current (PMDC) motor, which is a part of the electrical machines course. It is a software having a flexible structure and a graphical user interface (GUI). The virtual lab allows as a software tool monitoring the system's reaction in different operation conditions through graphs by changing the PMDC motor and controller parameters.

Key words: Fuzzy logic, DC motor, virtual laboratory, educational tool, software tool.

INTRODUCTION

In today's world, review of course contents and course delivery methods have become a necessity in parallel with the developing technology. Developments in conventional engineering subjects like electrics, electronics, mechanics, building and chemistry made it necessary to make new day-to-day additions to course contents. Preparation of the new additions made or to be made in parallel with the improvements in these engineering branches ensures better understanding and quicker learning of subjects by students. In education, backing theoretical knowledge with practice increases the speed of learning and ensures a permanent learning. Expensive laboratory systems are needed to be able to attain practical skills. Efforts are made to address this need by many simulation package programs developed for educational purposes allowing a more cost-effective and suitable learning environment. Package programs developed for educational purposes are not sufficiently flexible and interactive for different branches of science. This is why some educators prefer simulation package programs with unique graphical user interface and a more flexible structure (Moreno et al., 1995; Montero-Hernandez et al., 1999; Yigit and Elmas, 2008; Akcayol et al., 2004; Elmas and Sönmez, 2008; Gokbulut et al., 2006).

DC motors are being widely used in many industrial areas including household appliances, automotive, vehicles, space and aeronautics because they are easily controlled and offer a high performance (Sen, 1990). Speed control of DC motors was initially realized in 1891 by Ward Leonard by voltage control method (Chan, 1987). Conventional control methods applied for the speed control of DC motors have a nonlinear effect. Conventional controllers have poorer performances due to the non-linear features of DC motors like saturation and friction (Tipsuwan and Chow, 1999; Khoei et al., 1998; Lin et al., 1994).

If the aim is to get high performance by proportional

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(P), proportional integral (PI) and proportional integral derivative (PID) methods, which are conventional control methods, these systems need to be well-defined. A suitable mathematical model of the entire system needs to be produced in order to control a system. It is impossible to make the complete mathematical modeling of nonlinearly-structured systems. Variables of these systems may not be known as precise as to allow for making a mathematical modeling or these variables may change by the time. The structure of the FLC has adaptable features. Because of this feature, it is possible to ensure that the system gives strong responses against imprecision, parameter changes and load distributions. Fuzzy logic or fuzzy set theory was first formulated by Zadeh. With the introduction of FLC, many researchers worked on modeling of complex systems and made wide use of fuzzy logic controllers (FLC) in controlling well-defined, nonlinear and imprecise systems (Tipsuwan and Chow, 1999; Khoei et al., 1998; Lin et al., 1994; Zadeh, 1965; Akçayol et al., 2002; Lee, 1990).

FLC topics were included in the power electronics and electrical machines courses in universities due to FLC's successful applications in nonlinear systems. FLC courses are being given in the graduate and/or postgraduate degree programs of many universities. Expertise and specialization are required for FLC applications in complex systems generally requiring more time for learning and application. The best solution in choosing control parameters is to achieve this by trial and error method in simulation environment. Here, students can make real experiments in laboratory environment in order to verify, interpret and discuss simulation results (Akcayol et al., 2002).

Computer and internet technology offers the students, researchers and trainers many opportunities in today's world. There are many sites in the internet environment covering fuzzy logic and fuzzy logic controllers. There are also several software tools relating to fuzzy logic and artificial neural Networks (ANN). However, these tools are developed with a limited capacity and are unsuitable for application in electrical machines. One of the well-known commercial software tools is the MATLAB/Simulink software developed by Mathworks Inc. Although students using this software tool are able to learn the designs of conventional and FLC systems in their modeling operations, such a learning is limited only to several number of advanced level students. These software solutions do not save time in learning fuzzy logic controlled electrical machine drivers (Akcayol et al., 2002).

In this study, a virtual lab with a fuzzy logic controlled PMDC motor is developed. This virtual lab is software consisting of simulations of conventional (PI, PID) and fuzzy logic controlled models for speed control of the PMDC motor. The project was developed at the Department of Electronic–Computer Education, Faculty of Technical Education, Suleyman Demirel University. The software was written using the C# programming language in Microsoft Visual Studio 2008 environment. The software tool has a flexible structure and a graphical user interface. It is possible to monitor circuit reactions under different operation conditions by graphs by easily changing the motor and controller parameters of the driver.

MATHEMATICAL MODEL OF THE PMDC MOTOR

The equivalent circuit of the PMDC motor is given in Figure 1 (Lysshevski, 2003; Krishnan, 2001). Armature flow and rotor angular speed status equations of the PMDC motor are given in matrix form in Equation 1 electromagnetic moment is given in Equation 2 and back electromotor force is given in Equation 3.

$$\frac{d}{dt}\begin{bmatrix} i_a \\ \omega_r \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ \frac{K_t}{J} & -\frac{B_m}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix} \begin{bmatrix} U_a \\ T_L \end{bmatrix} \quad (1)$$

$$T_e = K_t \, i_a \quad (2)$$

$$E_a = K_b \, \omega_r \quad (3)$$

In the above-given equations; i_a is armature flow (A), ω_r rotor angular velocity (rpm), R_a armature resistance (Ω), L_a armature winding inductance (H), K_b back EMF constant (V/(rad/s)), K_t moment constant (Nm/A), J motor inertia (kg.m^2), B_m friction coefficient (Nm/(rad/s), U_a armature voltage (V), T_L load moment (Nm), T_e electromagnetic moment (Nm) and E_a back EMF (V).

FUZZY LOGIC CONTROLLER

Recently, the fuzzy logic introduced by Zadeh had a wide usage in different areas of application (Zadeh, 1965). A fuzzy logic controller consists of four parts including a fuzzification, fuzzy inference, knowledge base and a defuzzification part. Fuzzification is the process of transforming control input information received from the system into symbolic values which are verbal variables. Linguistic terms of fuzzy logic are generally expressed with the If-Then rule. Fuzzy inference is also named as the decision-making unit. Fuzzy logic is the core of control. Knowledge base is divided into two, being data-base and rule-base. Creation of the data-base requires

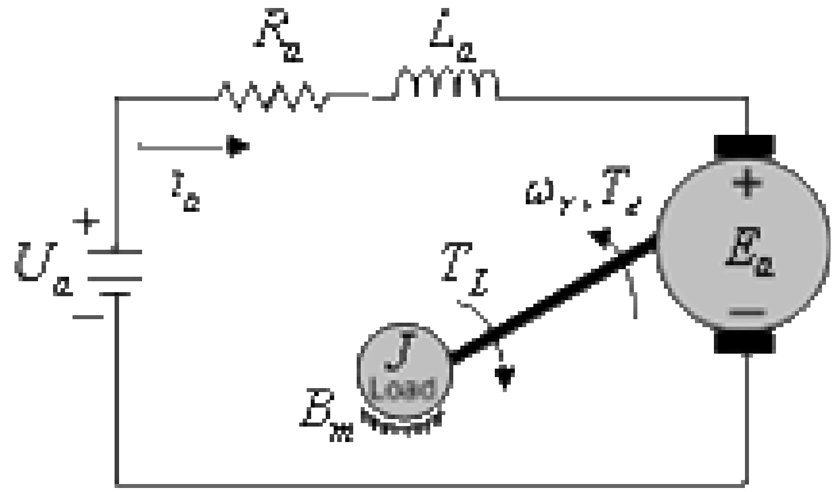


Figure 1. The equivalent circuit of the PMDC motor.

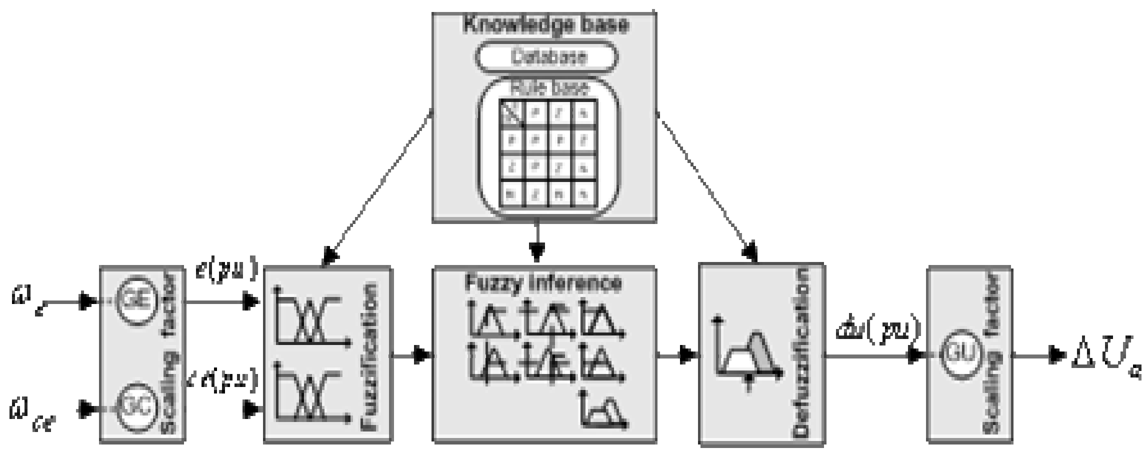


Figure 2. Fuzzy logic speed controller block diagram.

the definition of the universal set for each input and output variable, determination of the number of fuzzy sets and designing of membership functions. The rule-base consists of control rules detecting the behaviors of fuzzy logic controllers determined by experts. The result of fuzzy inference is a fuzzy set. In order that this result can be reapplied to the system, it should be converted into a numerical value such as an input value. This process is called defuzzification. The block diagram of fuzzy logic speed controller is shown in Figure 2.

SPEED CONTROL OF A PMDC MOTOR

Conventional PI, PID controller and FL controllers were applied to ensure the speed control of the motor in the PMDC motor driver system.

Conventional speed control of PMDC motor

Input variable of the Conventional PI (Proportional + Integral) and PID (Proportional + Integral + Derivative) controllers is defined as the speed error (ω_e) between reference speed (ω_r^*) and the actual motor speed (ω_r). Voltage (ΔU_a) is chosen as the output variable. Figure 3 gives the block diagram of PI and PID controllers of the PMDC motor. Equation 4 gives the speed error.

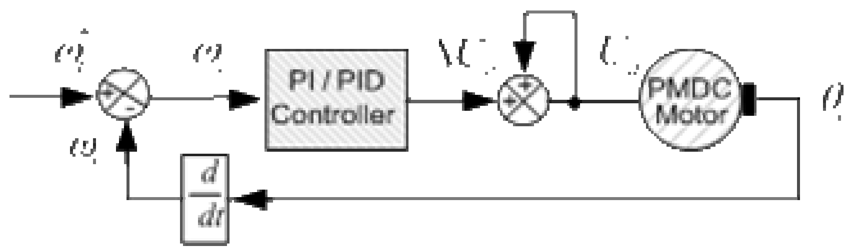


Figure 3. Conventional speed control of the PMDC motor.

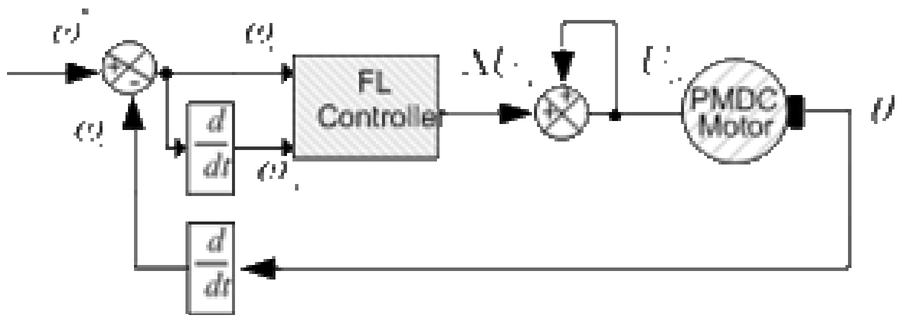


Figure 4. Fuzzy logic speed control of PMDC motor.

$$\omega_e(k) = \omega_r^*(k) - \omega_r(k) \quad (4)$$

PI and PID controllers

PI control is formed by two basic components. These are proportional and integral components. These components are expressed one coefficient each in the PI control algorithm. Mathematical expression of the PI control is given in Equation 5. PID control is formed by three basic components. These are; proportional, integral and derivative components. These components are expressed one coefficient each in the PID control algorithm. Mathematical expression of the PID control is given in Equation 6. These coefficients are generally named as proportional coefficient (Kp), integral coefficient (Ki), and derivative coefficient (Kd).

$$\Delta U_a = K_p \omega_e(k) + K_i \sum_{j=0}^{k} \omega_{ej} \quad (5)$$

$$\Delta U_a = K_p \omega_e(k) + K_i \sum_{j=0}^{k} \omega_{ej} + K_d(\omega_e(k) - \omega_e(k-1)) \quad (6)$$

The differential expression of the PI and PID controller in the computer application is given in Equation 7.

$$U_a(k) = U_a(k-1) + \Delta U_a(k) \quad (7)$$

Fuzzy logic speed control of PMDC motor

FLC input coefficients are defined as the speed error (ω_e) between the reference speed (ω_r^*) and the actual motor speed (ω_r) and as the change in speed error (ω_{ce}). Equation 8 gives the change in speed error. Voltage (ΔU_a) is chosen as the output variable change. Figure 4 gives the block diagram of the fuzzy logic controller of PMDC motor.

$$\omega_{ce}(k) = \omega_e(k) - \omega_e(k-1) \quad (8)$$

The reference speed required at the $\omega_r^*(k)$ k'th sampling time is the motor speed at the $\omega_r(k)$ k'th sampling time, and the motor speed error $\omega_{ce}(k)$ at the $\omega_e(k)$ k'th sampling time is the change in motor speed error at the k'th sampling time and $\omega_{ce}(k-1)$ is the change at the motor speed error at the $(k-1)'$ th sampling time.

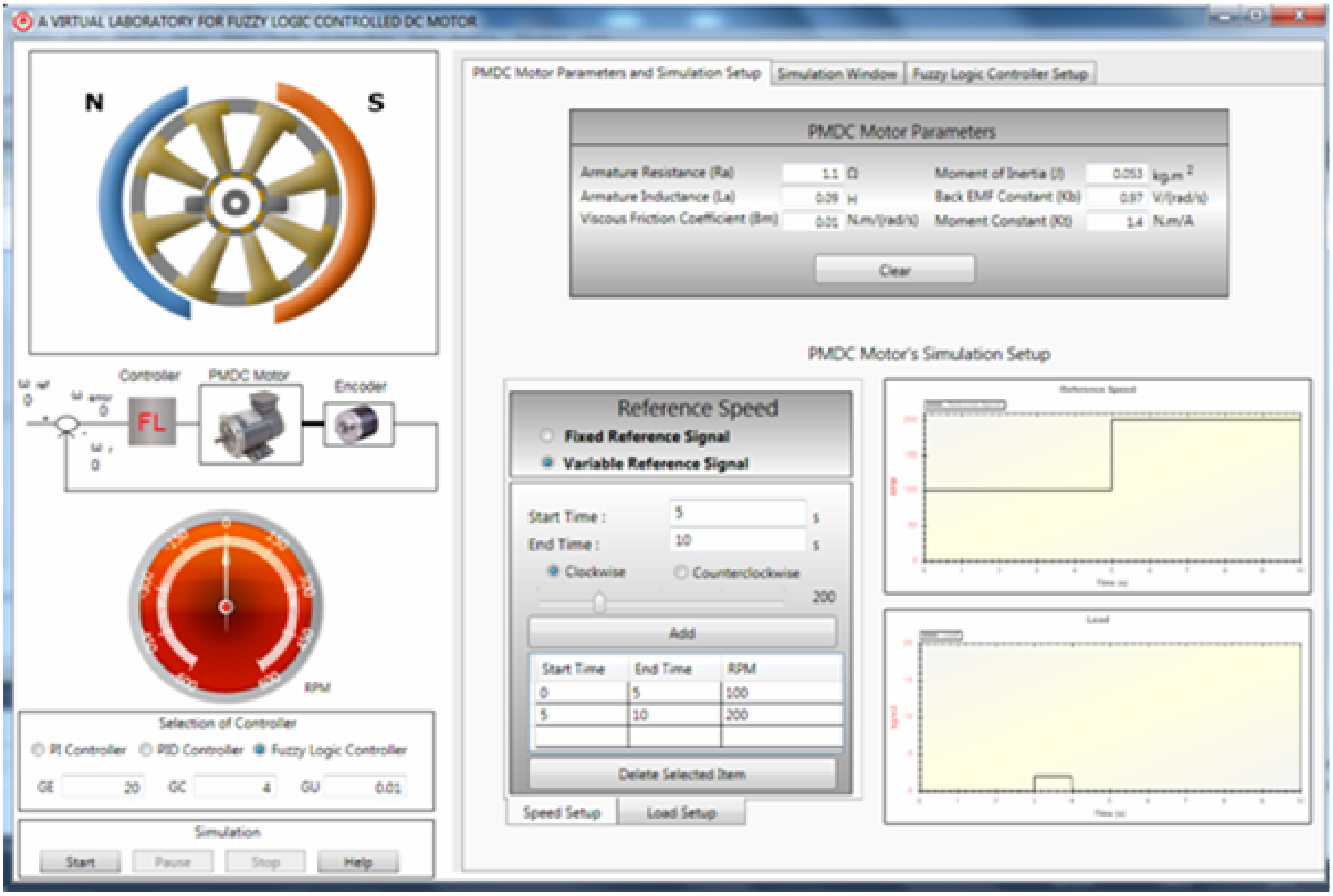


Figure 5. Main window of virtual lab.

The variables are represented as unit value [-1 1] in order to ensure flexibility in design and accurately adjust the controller. Scaling factors are used to make sure the controller's input and output variables are unit values (pu). These scaling factors are named as GE, GC and GU. Scaling factors in Figure 2 are shown in fuzzy logic speed controls. Variables explained as unit value are given in Equation 9.

$$e(pu) = \omega_e(k)/GE$$
$$ce(pu) = \omega_{ce}(k)/GC \qquad (9)$$
$$du(pu) = \Delta U_a(k)/GU$$

The order of operation for speed control is as follows:

1. PMDC motor's speed mark is sampled. 2. The speed error and the change in speed error are calculated. 3. Fuzzy sets and membership functions are set for the speed error and the change in speed error. 4. Change in the control function (ΔU_a) is set depending on each rule. 5. Actual change ΔU_a in (U_a) is calculated using the defuzzification method.

6. Change in the control function $U_a(k) = U_a(k-1) + \Delta U_a(k)$ is sent to control the motor.

VIRTUAL LABORATORY FOR FLC OF PMDC MOTORS

The virtual lab is developed using the C# programming language in Microsoft Visual Studio 2008 environment and it operates in Windows environment. Operations of the driver system can be observed on the computer screen and are adjustable by choosing the right windows.

The control window and the other window chosen can be simultaneously seen by pressing the button on the upper part of the screen. The main program's program window view is shown in Figure 5. The main window is divided into two parts. These are the control window on the left of the screen and the menu screen on the right of the screen. When the program is in operation, no changes are made in the content of the control window. The operation of the entire system can be observed in

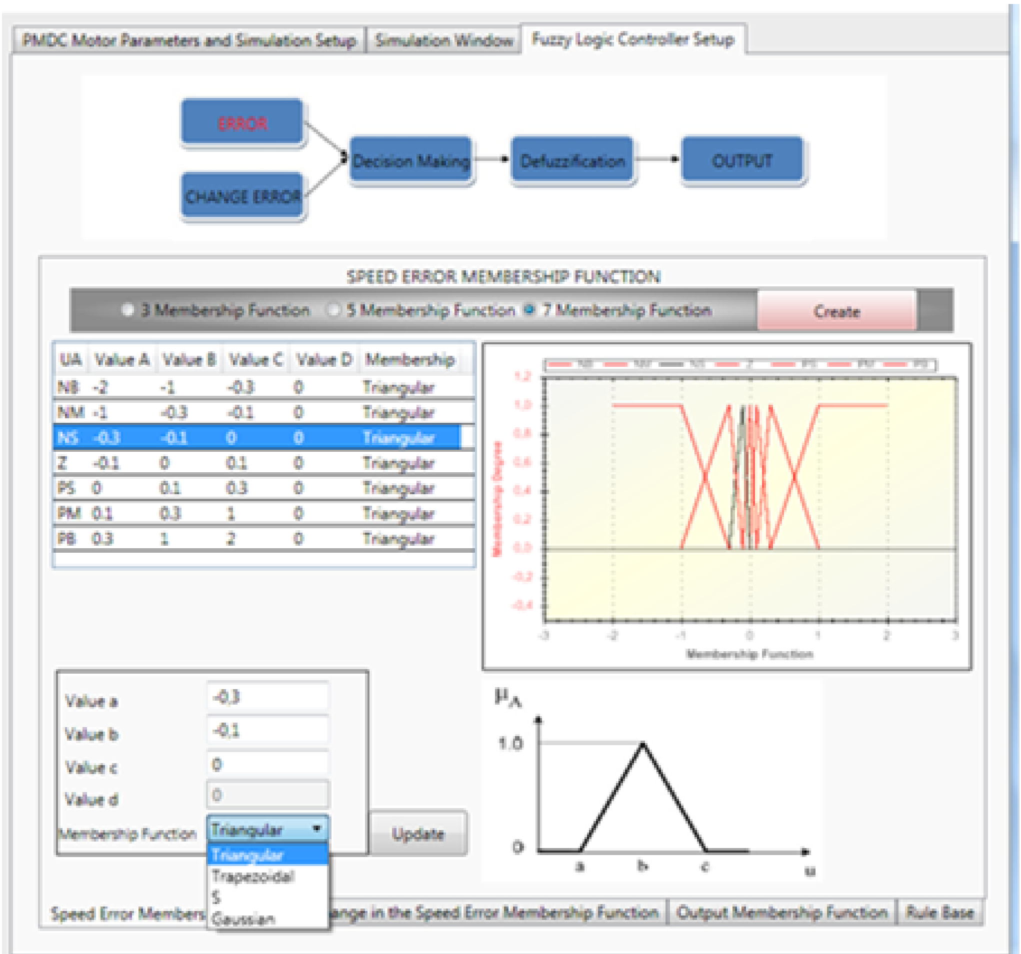


Figure 6. Fuzzy logic controller setup window.

the control window (e.g. operation of the PMDC motor, simulation time, reference and actual speed values of the motor and speed error). Controller selection (PI controller, PID controller and FL controller) can be made at the bottom of the control window. At the same time, the simulation process can be controlled by using buttons at the bottom-most part of the control window. The “Start” button starts the simulation, The “Pause” button pauses the simulation, the “Stop” button stops the simulation and the “Help” button is used to get help about the virtual lab.

The Menu window has three sub-windows, with contents changing according to the window selected on the menu. When one of the windows is selected, the selected window replaces the preceding window. These windows are shown in Figures 5,6,7,8 and 9. A student may directly start the simulation using a specific given PMDC motor and the default values for the FLC. Besides, the parameters of the motor and the FLC can be entered by the user to start a new simulation.

The motor and FLC setup windows allows the user to define the motor and FLC parameters. Motor and FLC parameters must be defined before starting the simulation.

PMDC motor parameters and simulation setup window

Figure 5 shows the PMDC motor parameters and simulation setup window. This window defines the motor’s electrical parameters, load parameters and reference speed. For example, a motor can be started in no-load or different load conditions depending on the type of load selected. At the same time, he can define a user speed function and load function at the set time range throughout the simulation time.

Fuzzy logic controller setup window

FLC setup window is shown in Figure 6. Fuzzy logic controller parameters are defined in this window. FLC setup window has four sub-windows, with contents

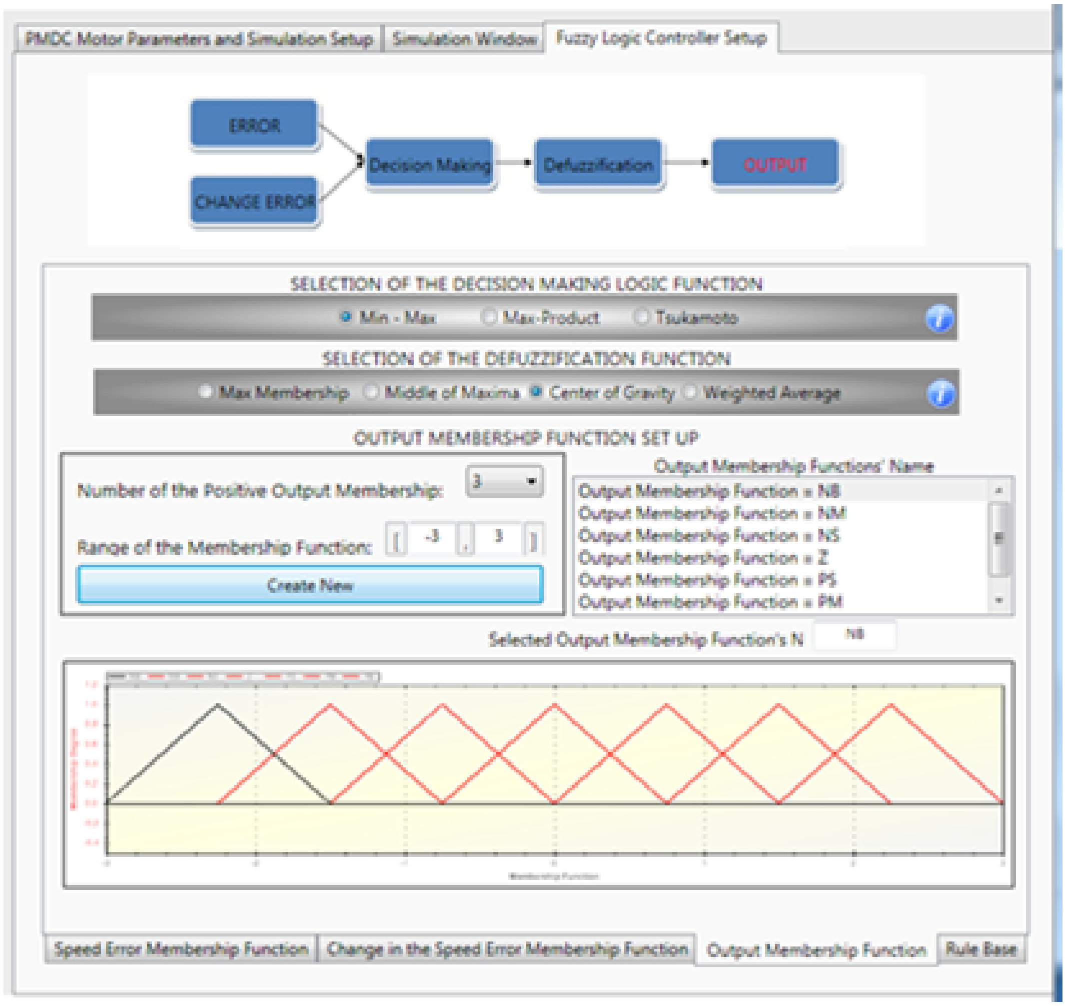
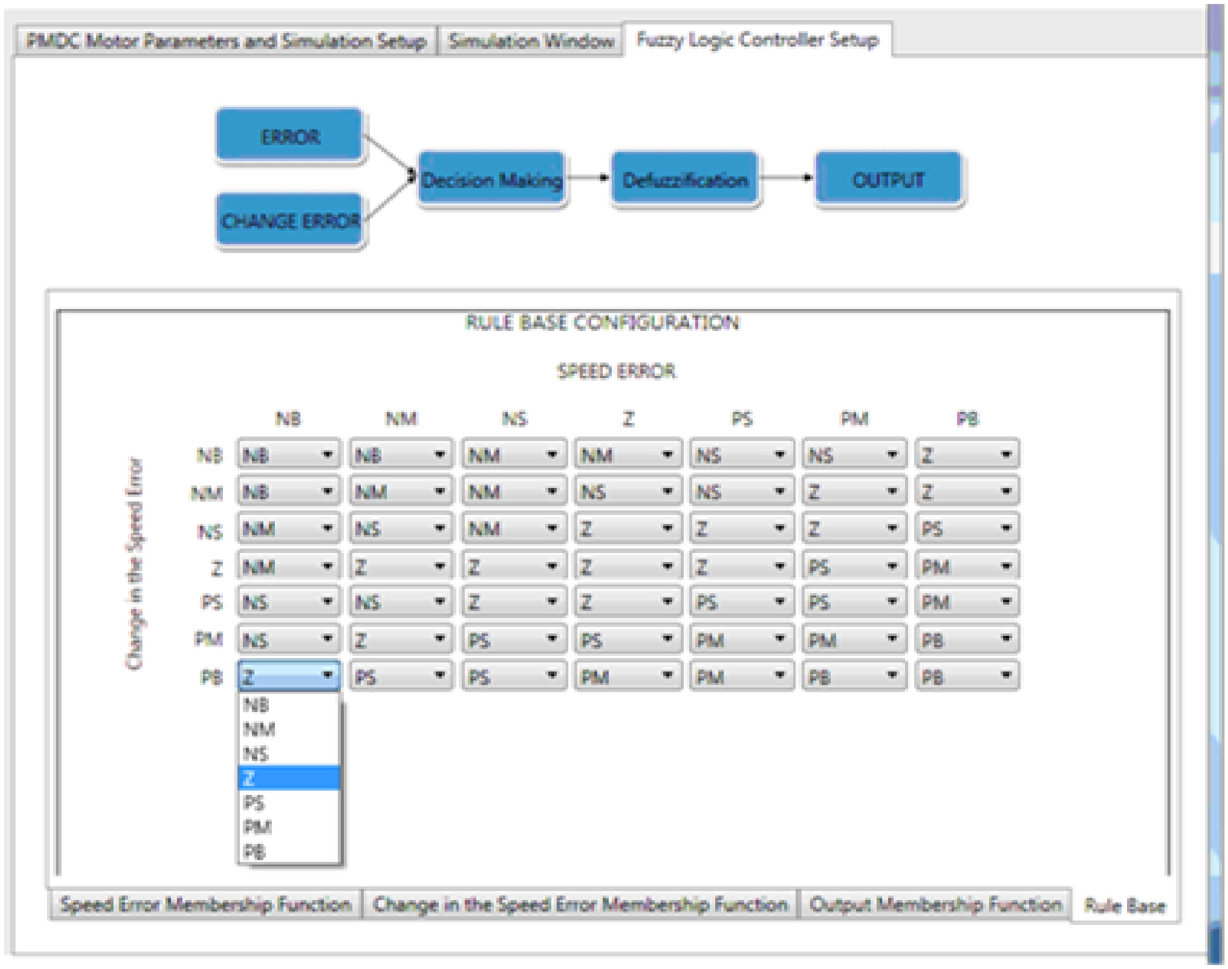


Figure 7. FLC output membership function setup window.

changing depending on the window selected. When one of the windows is selected, the selected window replaces the preceding window. These windows are at the bottom-most part of the FLC setup window. These are the speed error membership function, change speed error membership function, output membership function and the rule base windows. For speed error membership function, first one of the 3, 5 or 7 membership functions is selected to create the membership function. Four types of membership functions are given for the speed error membership function. These are “Triangular”, “Trapezoidal”, “S” and “Gaussian” functions. Each membership function can be defined by the user. Whatever membership function is selected, values of the selected membership function are defined in the window. These values can be changed by the user if desired. The speed error membership function can only consist of a membership function, any two of them, any three of them, or any four of them. All operations carried out for the speed error membership function should be made for the change speed error membership function as well.

The output membership function, which is the third sub-window in the FLC setup window, is shown in Figure 7. The fuzzy inference, decision making, defuzzification methods and output membership function are defined in this window. Three types of fuzzy inference methods are given for the fuzzy inference. These are the “Min max”, “Max product” and the “Tsukamoto’s” methods. Four defuzzification methods are given in the defuzzification operation. These are the “Max membership”, “Middle of Maxima”, “Center of gravity, and the “Weight average” methods. Further information about these methods can be obtained from the (i) icon next to them. 3 to 15 membership functions can be selected for the output membership function. In the output membership function only the triangular membership function is used. Triangular membership functions are symmetrical. Labels of the membership functions can be changed if desired. For example, Negative Medium can be written instead of the NM membership function.



	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	Z
NM	NB	NM	NM	NS	NS	Z	Z
NS	NM	NS	NM	Z	Z	Z	PS
Z	NM	Z	Z	Z	Z	PS	PM
PS	NS	NS	Z	Z	PS	PS	PM
PM	NS	Z	PS	PS	PM	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB

Figure 8. FLC rule base setup window.

The rule-base, which is the fourth sub-window in the FLC setup window, is shown in Figure 8. The number of rules in the table of rules changes depending on the speed error membership function and change speed error membership function. For example, the number of the speed error membership function membership and the number of the change speed error membership function membership are selected as 7. In this case, the number of rules needs to be defined as 7x7, which makes 49 rules in total. The user can change the table of rules as it is desired.

The simulation and help window

The simulation, which is the third sub-window in the menu window, is shown in Figure 9. In the upper part of this window are the graphs showing the PMDC motor speed and the change of flow by time. By clicking the right mouse on these graphs, it is possible to select the show point values on graph, un-zoom, undo all zoom/pan and set scale to default functions as well as the graph copy, save image as, print functions. Weight distribution is given for speed error membership function and for change speed error membership function in the middle of the window. The change in the defuzzification can be seen throughout the simulation time depending on the defuzzification method selected at the bottom left of the window. Lastly, the distribution of rules of the table of rules is seen in the bottom right of the window. This menu contains detailed help information about the virtual lab.

EVALUATION OF THE VIRTUAL LABORATORY

The PMDC motor and its control is an integral part of the electrical machines labs applications included in the renewed course curricula in the electrical engineering and electrical education departments of universities and in vocational high schools. In conventional laboratory experiments, students carry out an experiment on their own by forming student groups due to the lack of time, resources and sufficient number of lecturers (Yigit and

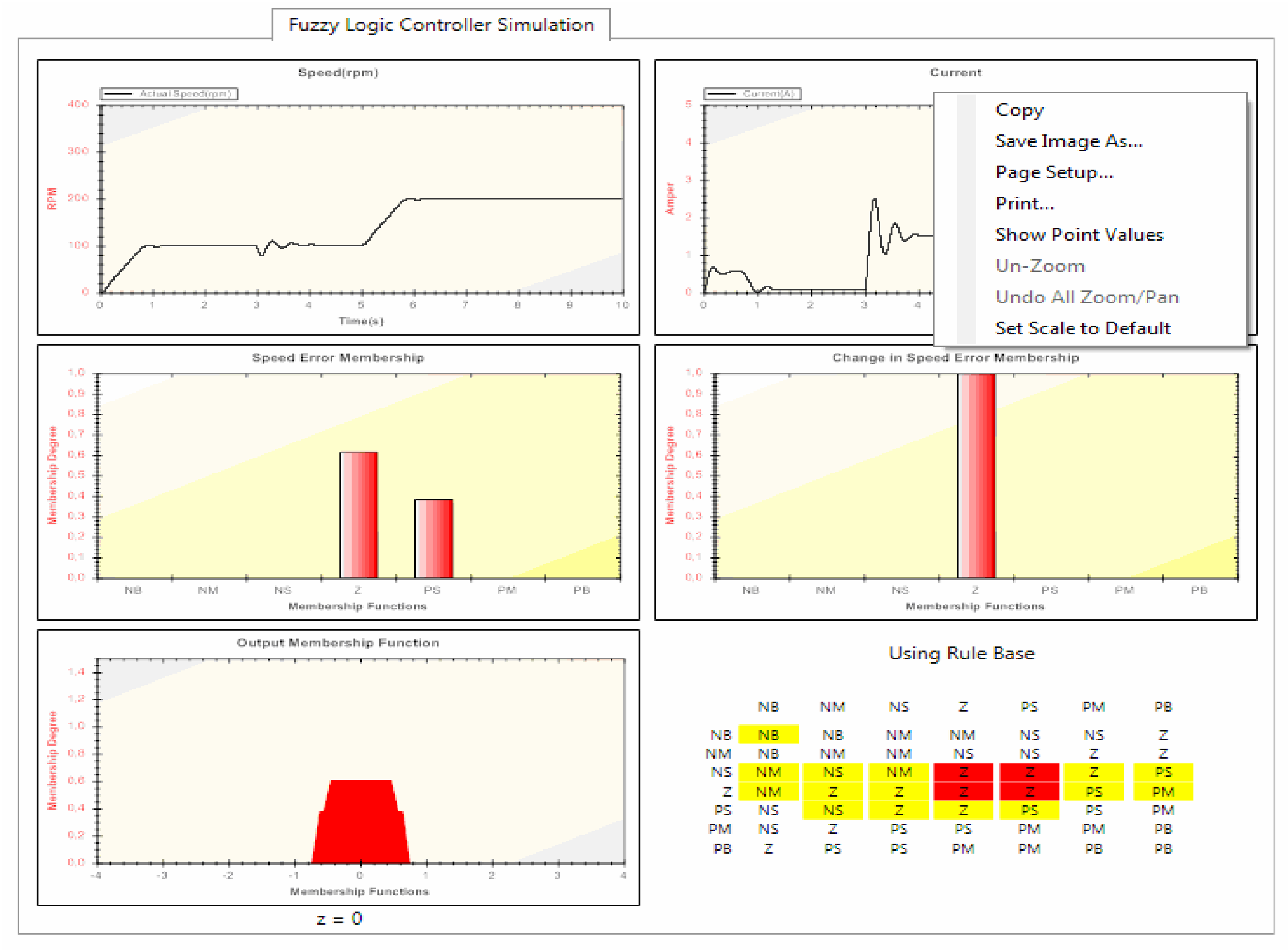


Figure 9. FLC simulation window.

Elmas, 2008). Student groups generally consist of 4 or 5 persons. However, in larger student groups, students fail to get sufficient information about the experiment. This virtual lab ensures overcoming the difficulties mentioned herein.

With this software tool, the students need to have theoretical information in relation to the course before the study about conventional PI, PID and Fuzzy Logic controllers together with the structure of the PMDC motor, its operation principle, motor and driver model. As a result of the theoretical information obtained during the course, students are capable of easily conducting the relevant experiments and better their knowledge on the subjects with this virtual lab. Therefore, this virtual lab will give each student the chance to spend the required time on the tool, use different controls and learn how the PMDC motor will react under various speed and load conditions.

CONCLUSIONS

This study presents a virtual lab for PMDC motor driver to ensure a cost-effective education and experience. Conventional PI, PID, and fuzzy logic controllers are used in the PMDC motor driver system. This virtual lab helps the students both in effectively understanding and improving the controllers and the PMDC motor. The software has a flexible structure and a graphical user interface. The user can easily change the driver's motor and controller parameters in various operational conditions. The software can easily be installed on a computer configured with Windows (Windows 98, ME, NT, XP, Vista, Windows 7).

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