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# PC based educational tool for a switched reluctance drive with fuzzy logic

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**Abstract** This paper introduces a PC based educational tool for a switched reluctance drive (SRD) with fuzzy logic which is prepared for undergraduate and graduate level students. The paper first describes how the switched reluctance drive system works. Then details are given of how to estimate the flux linkage by using fuzzy set theory. Finally an application of fuzzy logic control to an SRM drive is presented.

**Keywords** fuzzy logic controller (FLC); switched reluctance motor (SRM)

The switched reluctance motor (SRM) is one of the motors that attracted the attention of researchers in variable speed applications due to its advantages over conventional a.c. motor drives. Therefore, the electrical machinery course curriculum is being updated with the development of technology. SRMs and their control are being covered in revised course curricula, thus yielding an increase in the quantity of the material to be taught. However, this increase in quantity does not always lead to an increase in understanding.

Most of the difficulty in understanding the operation of the SRM stems from the double saliency of the motor. Neither the rotor nor the stator has a smooth cylindrical surface at the air gap, but both members have salient poles or teeth. Because of this feature, there is no pure steady state which is a series of transients in which the inductive circuit parameters of the phase windings are variable functions of both position and current. The variation with current is associated with intense saturation of the partially overlapping poles that is difficult to calculate in detail.<sup>1</sup> The use of a computer is promising for the improvement of this drawback. The presence of PCs offers hands-on laboratory experience to students at college, at home and also to distance-learning students at other universities.

Several methods have been reported in the literature related to the use of computers in modelling and simulation of the SRM by using software packages.<sup>2-8</sup> In Refs [3-8], a common circuit-based simulation program SPICE, later PSpice, currently OrCAD PSpice, a trademark of OrCAD Inc. (Beaverton, OR 97008-7137, USA) has been proposed for analysis and simulation of the SRM. In Refs [7-8] the professional software package, MATLAB-Simulink, developed by Mathworks, Inc. (Natick, MA 01760-2098, USA), has been proposed for dynamical simulation of the SRM. PSpice was mainly designed for circuit analysis. MATLAB was designed for engineering solutions. Although students may still use MATLAB and PSpice to create their own simulations in a sequence, the use of these programs might be time consuming for them. They do not give detailed information about how an SRM is to be modelled.

The SRM cannot be operated without a driver. SRMs are generally modelled by ignoring their magnetic nonlinearity; this approach makes the control system inefficient or poor. To overcome this problem fuzzy set theory is an alternative due to its usefulness in systems where it is difficult to obtain an accurate mathematical model or when the model is severely nonlinear.

In this paper, a PC based educational tool for a switched reluctance drive (SRD) with fuzzy logic (SRMDTool) is presented. The tool was prepared for undergraduate and graduate students. The paper first describes the basic operational principle and modelling of the SRM drive. Then details are given of how to estimate the flux linkage by using fuzzy set theory. Finally an application of fuzzy logic control to an SRM drive is presented.

### Operation of the SRM

The SRM is a very simple machine that uses salient poles on both stator and rotor, which are constructed from a single stack of laminations. The windings on the stator are of simple form and no windings are required on the rotor. The unwound rotor not only simplifies construction but opens the way for the use of drives with extremely low inertia. The price to be paid for this advantage is relatively complex control circuitry. However, this still compares favourably with other available drives, such as a.c. PWM drives. The SRM relies on the principle that its magnetic circuit can produce high torque and power output because of the large difference in minimum and maximum phase inductance. Figure 1 shows an arrangement of the SRM with 8 stator poles and 6 rotor poles including a bridge converter. In Fig. 1 only one phase connection is shown for convenience. By energising the stator phases at appropriate angular positions, the rotor may be moved around by simple magnetic attraction between the rotor teeth and the stator poles i.e., when phase 1 is energised the rotor moves.

During the conduction mode of phase 1 ( $Ph_1$ ), both switches  $S_1$  and  $S_2$  are in the 'on' state and thus energy is supplied to phase windings 1 and 1'. The conduction mode starts when the rotor and stator poles are unaligned  $\theta_{on}$ , so that phase current tends to reach reference current before the phase inductance increases as seen in Fig. 2.

When the phase current reaches the reference current, the converter works in current regulation mode. During current regulation mode, current is maintained at the reference value by switching both switches  $S_1$  and  $S_2$  on and off till  $\theta_{off}$  is reached. To initiate commutation both switches are turned off. When switches are off energy stored in phase windings is transferred to the d.c. supply via  $D_1$  and  $D_2$  that yields useful utilisation of the energy.

The recirculated energy in a drive with an applied voltage requires current flow and acts to increase the inverter and motor losses that accompany the current flow. It is possible to produce constant instantaneous torque by controlling instantaneous currents or flux linkages. The simplest and most commonly used control strategy for the SRM involves the use of angle and current amplitude modulation.

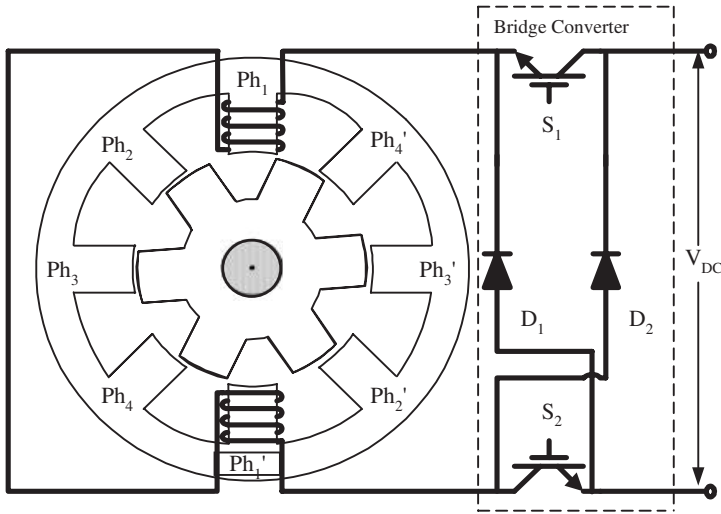


Fig. 1 An SRM with 8 stator poles and 6 rotor poles including bridge converter.

**Flux estimation of the SRM using fuzzy logic**

A brief review is included here to establish the notation. The voltages across the terminals of the machine are related to the phase currents and the flux linkage by the matrix equation

$$v = Ri + \frac{d\psi}{dt} \tag{1}$$

where  $v = [v_a, v_b, v_c, v_d]^T$  is the terminal voltage vector,  $i = [i_a, i_b, i_c, i_d]^T$  is the phase current vector, and  $\psi = [\psi_a, \psi_b, \psi_c, \psi_d]^T$  is the flux linkage vector.  $R$  is the diagonal matrix of phase resistance.

The behaviour of the SRM can be explained in terms of a set of flux/current/rotor position ( $\psi/i/\theta$ ) curves. These curves represent the variation of flux linkage with current for a set of rotor angles, and depend on the permeance of the air gap and iron parts of the magnetic circuit. In the unaligned position, the curve is linear and saturation is not present. On the other hand, in the aligned position, the curve is similar to that of a gapped core and the curve is not linear and saturation is present.

Figure 2 shows these curves for a typical machine. This curve may be obtained if a constant current is established instantly while the rotor is in the unaligned position and remains constant until the rotor reaches the aligned position where the current is removed instantly.

The torque produced by a switched reluctance motor is proportional to the rate of

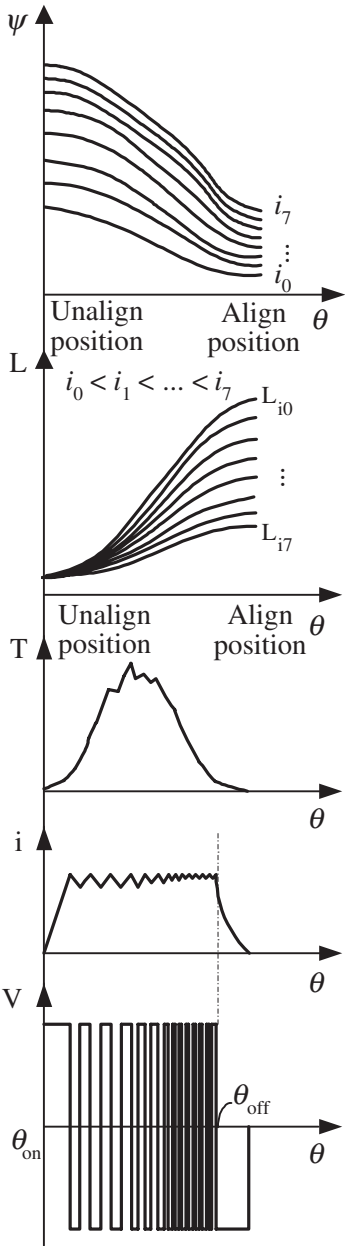


Fig. 2 One phase flux linkage, inductance, torque, current and voltage vs rotor position of the SRM.

change of coenergy as the rotor moves from one rotor position to another. In a device of this type, the most general expression for the instantaneous torque is:

$$T = \left( \frac{\partial W'}{\partial \theta} \right)_{i=\text{constant}} \tag{2}$$

Where  $T$  is torque,  $\theta$  is rotor position,  $i$  is phase current, and  $W'$  is the coenergy. The coenergy is a function of both rotor position and excitation current and therefore, the torque produced has to be expressed in terms of the flux linkages since

$$W' = -\int_0^i \psi di \tag{3}$$

where  $\psi$  is the flux linkage. When evaluating the partial derivatives, it is essential to keep the indicated variable constant. To estimate the flux linkage  $\psi(i, \theta)$  in the SRM by using fuzzy set theory,<sup>9</sup> the phase current  $i$  and the rotor position  $\theta$ , are employed. Figure 3 shows the configuration of the fuzzy logic flux estimator which is designed to process fuzzy quantities only. Therefore the crisp input values of  $i$  and  $\theta$  must be converted to fuzzy sets before being used. This process is called the fuzzification operation. The fuzzification process requires a 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, or another appropriate form.

The second process of the fuzzy logic flux estimator is the fuzzy inference engine 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 outputs of the fuzzy inference engine are fuzzy output variables. The fuzzy logic flux estimator must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables. This conversion is called defuzzification.

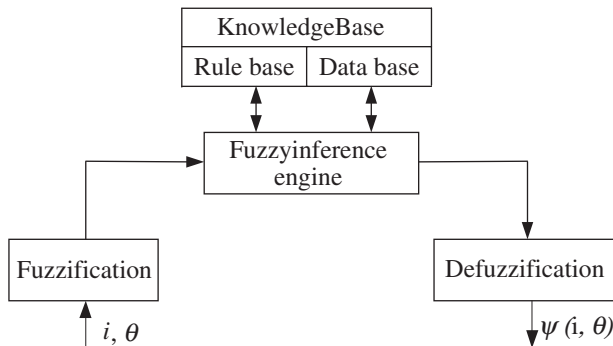


Fig. 3 The configuration of the fuzzy logic flux estimator.

Fuzzy output was calculated by using the max-min composition method. Then the crisp output of  $\psi(i, \theta)$  was determined by the height defuzzification method. In the height method, the centroid of each membership function for each rule is first evaluated. The final output  $\psi(i, \theta)$  is then calculated as the average of the individual centroid, weighted by their heights as follows:

$$\psi(i, \theta) = \frac{\sum_{i=1}^n u_i \mu(u_i)}{\sum_{i=1}^n \mu(u_i)} \tag{4}$$

$\mu(u_i)$  is a degree of membership associated with a fuzzy level of input  $u_i$ . The range of  $\mu(u_i)$  is from 0 to 1. Fuzzy input variables are current  $i$ , rotor position  $\theta$ . The output variable is the flux linkage  $\psi(i, \theta)$ . Nine fuzzy sets for the current, 7 fuzzy sets for the rotor position and 11 fuzzy sets for the flux are chosen. When constructing rules and membership functions, the same or close variables are taken into consideration to decrease number of rules and membership functions. The fuzzy rule base for flux estimator is given in Table 1.

A typical rule has the following structure:

If  $i$  is A1 and  $\theta$  is T4 then  $\psi(i, \theta)$  is P7.

The membership functions of the fuzzy variables ( $\theta, i$  and  $\psi(i, \theta)$ ) are shown in Fig. 4.

Due to 50 per cent overlap assumed for membership functions as shown in Fig. 4, the four rules are fired for the given inputs. Fuzzy output was calculated by using the max-min composition method. Then crisp output of the  $\psi(i, \theta)$  was determined by the height defuzzification method. The steps for fuzzy  $\psi(i, \theta)$  estimation are summarised as follows:

- 1 Sample the rotor position and phase current;
- 2 Determine the fuzzy sets and membership functions for rotor position and phase current;
- 3 Determine the fuzzy set of phase  $\psi(i, \theta)$  according to the individual fuzzy rule;
- 4 Calculate the actual  $\psi(i, \theta)$  by height defuzzification.

TABLE 1 Fuzzy rule base for flux estimator

$\theta$ $i$	T1	T2	T3	T4	T5	T6	T7
A1	P3	P4	P5	P7	P9	P11	P11
A2	P3	P3	P5	P7	P8	P10	P11
A3	P3	P3	P4	P6	P7	P9	P9
A4	P2	P3	P4	P6	P6	P7	P7
A5	P2	P2	P3	P5	P6	P6	P6
A6	P2	P2	P3	P5	P5	P5	P5
A7	P1	P2	P3	P4	P5	P5	P5
A8	P1	P1	P2	P4	P4	P5	P5
A9	P1	P1	P2	P2	P3	P4	P4

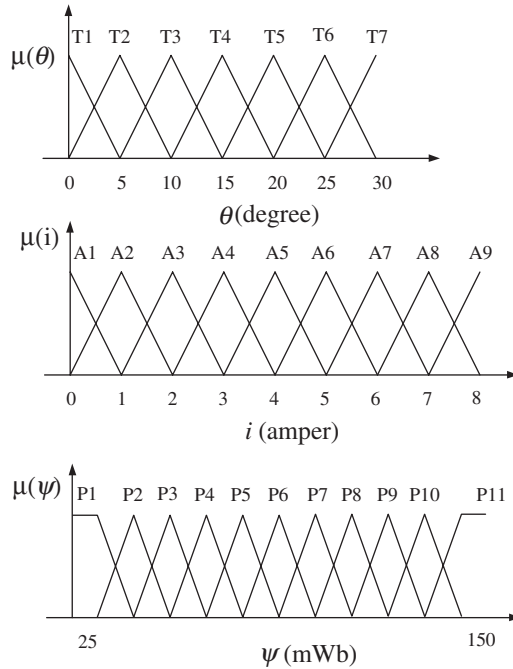


Fig. 4 The membership functions of  $\theta$ ,  $i$ , and  $\psi(i, \theta)$  variables.

**The fuzzy logic controller for the SRM**

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

$$J \frac{d\omega}{dt} = -B\omega + T - T_L \tag{5}$$

$$\frac{d\theta}{dt} = \omega \tag{6}$$

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

The fuzzy logic controller accepts speed error  $\omega_e$  and change in speed error  $\omega_{ce}$  as input variables. The output variable is change in the reference current  $\Delta_i$ . The speed error  $\omega_e$  and change in speed error  $\omega_{ce}$  are defined as:

$$\omega_e = \omega^* - \omega \tag{7}$$

$$\omega_{ce} = \omega_e - \omega_{e0} \tag{8}$$

where  $\omega^*$  is the reference speed,  $\omega$  is the actual speed,  $\omega_{e0}$  is the previous speed error. The block diagram of the fuzzy logic controlled SRM drive system is presented in Fig. 5.

The control unit consists of a fuzzy logic controller and a switching signal generator (turn-on angle  $\theta_{on}$ , turn-off angle  $\theta_{off}$ , and pulse width modulation duty cycle). The fuzzy logic controller output is change in the current  $\Delta_i$ . Feedback signals are the position  $\theta$  and speed  $\omega$ , and the phase currents  $i_{a,b,c,d}$  are measured. In this application, the position signal is used to calculate the speed. The membership functions of  $\omega_e$ ,  $\omega_{ce}$ , and  $\Delta_i$  are shown in Fig. 6.

The defuzzifier collects the fuzzy outputs from all rules to derive the actual crisp output  $\Delta_i$  based on the following equations:

$$\Delta_i = \frac{\sum_{i=1}^n \mu(u_i) \cdot u_i}{\sum_{i=1}^n \mu(u_i)} \tag{9}$$

The range of  $\mu(u_i)$  is from 0 to 1. Reference current ( $i^*$ ) is defined as

$$i^* = i_0^* + \Delta_i \tag{10}$$

where,  $i_0^*$  is the previous reference current. The steps for speed control are summarized as follows:

- 1 Sampling of the position signal of the SRM;
- 2 Calculation of the speed error and the change in speed error;
- 3 Determination of the fuzzy sets for the speed error and the change in speed error;
- 4 Determination of the control action  $\Delta_i$  according to individual fuzzy rule;
- 5 Calculation of the actual change of  $i$  by centroid defuzzification method;
- 6 Sending the change of control action  $\Delta_i$  to control the drive.

**Evaluation of the educational tool**

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,

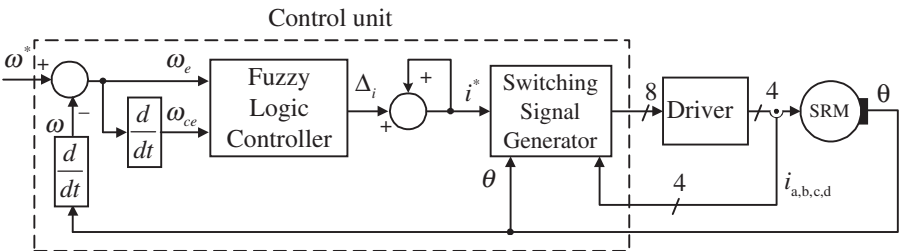


Fig. 5 Fuzzy logic controlled SRM drive system.

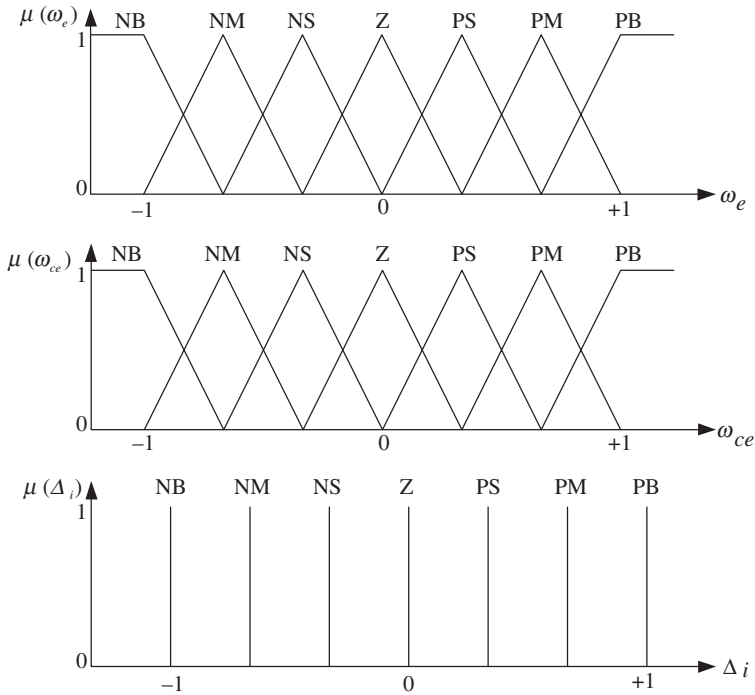


Fig. 6 Membership functions of  $\omega_e$ ,  $\omega_{ce}$ , and  $\Delta_i$ .

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 such laboratory exercises is that the individual student is unable to perform a test him- or herself because of limited time and resources. Generally, the laboratory assignments only require 3–4 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 is not adequately demonstrated over its working range.

The first exposure of the tool to student usage was in a fourth-year electrical engineering course of 25 students, in which one of the modules taught focused on the SRM. One of the laboratory assignments was an actual SRM with fuzzy logic controller. Before studying with the tool, the students are required to attend four two-hour theoretical sessions. Two sessions were about the SRM's construction, operation principle, modeling of the motor and the drivers. One session was about fuzzy set theory and the fuzzy logic controller. In the last session, a two-hour lecture is allocated for the description of the tool.

After lectures on fuzzy logic, the students performed a series of tests with the educational tool and presented the results in a report with a one-week deadline. The stu-

dents were asked to obtain a fuzzy logic controller for the SRM drive system and to report the results. The educational tool being discussed is similar to what was prescribed for the actual SRM test. Hence, it was intended that the tool assignment would provide a reinforcement of what was expected for the actual test as well as giving each student the opportunity to spend time with the tool and obtain a thorough understanding of the responses of the SRM under different speeds and loads. Then students were conducted to the motor-control lab where the SRM is driven by a bridge converter which is controlled by the TMS320F240 DSP set to observe operation and control of the SRM.

The tool is expected to achieve the following educational goals. One who uses this tool should be able to:

- understand the basics of the SRM drive system given in lectures;
- relate system parameters to system response;
- do virtual experiments on a PC to be ready for real laboratory experiments;
- improve his/her knowledge on fuzzy control;
- develop an appropriate fuzzy rule base for the drive system;
- save time while developing his/her knowledge.

Afterwards results obtained by use of the tool and results obtained without using the tool were compared. Student response to the use of the tool was obtained through evaluation sheets. The feedback from the introduction of the educational tool was very positive. The scores for the laboratory assignments were higher than previous years and the understanding of this material seemed to be more uniform across the class as a whole. The lecturers may also develop new ideas and teaching methods by using the tool. With this philosophy, the aim is that the tool is available for everyone who wants to use or try it so that students may use it in a laboratory or at home.

### **Usage of the educational tool**

The main window is divided into two sections, namely the navigation window, which is on the left and the menu window on the right as seen in Fig. 7. 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. The menu window has five sub-windows and the contents of the menu window change according to the window chosen from the menu at top of the screen. When one of the windows is chosen, the chosen window replaces the previous menu window. In the SRM setup window, motor and load parameters are defined. In the FLC setup window, fuzzy controller parameters are defined. The SRM graphics window shows speed, current and voltage of the SRM. In the FLC graphics window, distribution graphics for rule base, weight distribution for speed error and weight distribution for change in error are given. The simulation window 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 defuzzification which uses the height method. In addition on the left of

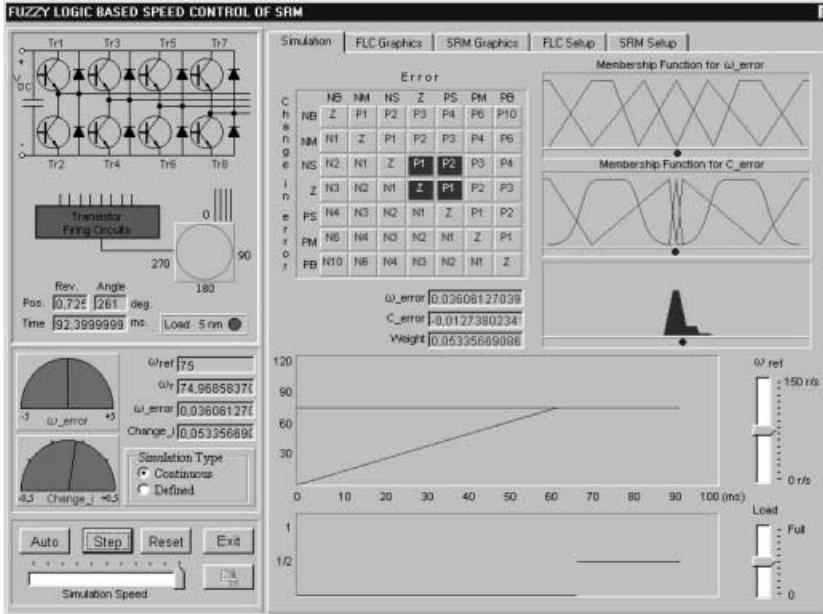


Fig. 7 The main window (navigator on the left and menu on the right).

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.

**Conclusions**

This paper introduces an educational tool for a fuzzy logic controlled SRM drive to help students to improve their understanding on both the SRM drive and the FLC. The tool describes the basic operation of the SRM drive, fuzzy logic flux estimator and application of fuzzy logic speed control to the SRM. Anyone who is interested in the SRM, the FLC and the FLC controlled SRM may use the tool in a laboratory or at home. Students may practise on the drive system, interpreting and drawing conclusions related to system parameters by changing motor and controller parameters under different operating conditions. The feedback from the student who used the educational tool was very positive. The tool also encourages self-learners. SRMDTool is available from the authors at no cost by sending an e-mail to celmas@gazi.edu.tr.

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