Fuzzy Logic Control of Food Frying Process: Motor Speed Control of Food Frying Process

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ABSTRACT

The control of the rotation speed of motors is very complicated when done using traditional control techniques, as it requires a very complex mathematical model. Using Fuzzy logic eliminates the need for mathematical modeling and allows easy realization of a solution.

In this study, we evaluate the effects of fuzzy control parameters on speed control of DC servomotor of food frying process control. Motor speed control of food frying experiments is conducted under no load and load-varying conditions. The control accuracy is of a high level, and has a fast response time. Furthermore, the fuzzy logic controller is analyzed and the speed control system of brushless DC Motor is implemented. To acquire an accurate fuzzy logic control algorithm, a simulation with the MATLAB® program was made, while the performance of the system, done with an experiment for a unit step response, was also verified.

(Keywords: fuzzy logic, brushless DC motor, servomotor control, fuzzy reasoning system, high efficiency control)

INTRODUCTION

The fuzzy logic algorithm consists of three steps:

1) Fuzzification,
2) Fuzzy Inference
3) Defuzzification

In this paper, seven fuzzy sets are defined for the input values Error (E) and Change in Error (CE) analyzing the motor speed control of food frying process:

1) NB: negative big
2) NM: negative medium
3) NS: negative small
4) ZE: zero equal
5) PS: positive small
6) PM: positive medium
7) PB: positive big.

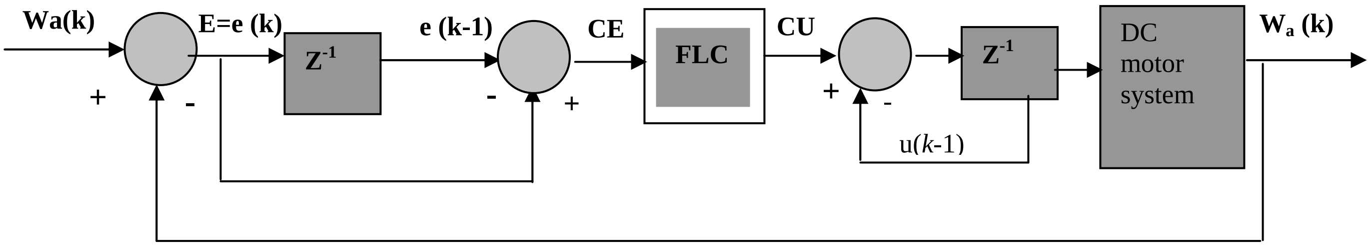
For the speed control of DC motors used in the food frying processl, some experts have adopted fuzzy a control technique [1-4,10]. Recently, a brushless DC Motor has been in increased demand due to preciseness of industrial technology and increase of various kind of control devices. A brushless DC Motor is suitable as a servo motor because of its high efficiency and excellent control characteristics[6]. A controller for a brushless DC Motor, with a high level of quality is analyzed. In this paper, a fuzzy reasoning algorithm was adapted which responded well to various levels of loading.

Figure 1 is the block diagram of FLC as applied to the DC motor system that controls the speed of the food frying conveyor belts. Therefore, the result from a P-I controller is initially borrowed as a priori knowledge in the design process. The performance of the FLC is then improved by adjusting the rules and membership functions. These design procedures are described in this paper.

BRUSHLESS DC MOTOR

Brushless Motor Construction

DC brushless motors are similar in performance and application to brush-type DC motors. Both have a speed vs. torque curve which is linear, or nearly linear. The motors differ, however, in construction and method of commutation. A brush-type permanent magnet DC motor usually consists of an outer permanent magnet field and an inner rotating armature.



$E = e(k) = \omega_r(k) - \omega_a(k)$, $CE = e(k) - e(k-1)$, $CU = u(k) - u(k-1)$ Where k is the time index

Figure 1: Block Diagram of Fuzzy Logic DC Motor.

A mechanical arrangement of commutator bars and brushes switches the current in the armature windings to maintain rotation. A DC brushless motor has a wound stator, a permanent magnet rotor assembly, and internal or external devices to sense rotor position. The sensing devices provide signals for electronically switching (commutating) the stator windings in the proper sequence to maintain rotation of the magnet assembly. The rotor assembly may be internal or external to the stator in a DC brushless motor. The combination of an inner permanent magnet rotor and outer windings offers the advantages of lower rotor inertia and more efficient heat dissipation than DC brush-type construction. The elimination of brushes reduces maintenance, increases life and reliability and reduces noise and EMI generation.

Brushless Motor Commutation

The possible number of phases and winding arrangements for the DC brushless stator are quite varied. As in the case of brush-type DC motors, increasing the number of phases reduces torque ripple. However, an important practical consideration for DC brushless motors is the number of electronic switches required to commutate the phases. Three phase motors provide a compromise in this regard and are popular in many applications. The winding arrangement for a three phase motor may be either a Y or a Δ configuration. The most efficient operation of the motor requires current flow in more than one phase at any instant and current reversal in each of the phases at some point during 360 electrical degrees of rotation. This is turn requires a minimum of two electronic switches per phase. It may be noted that the Y configuration with a lead common to the three phases can be commutated in a unipolar mode with only three electronic switches. However, the motor torque is reduced with this scheme.

Hall Effect Commutation

Rotor position sensing is essential for proper commutation of DC brushless motors. Magnetic sensing with inexpensive Hall effect switches is frequently adequate. The devises require little space and can easily be placed within the motor. Optical encoders or resolvers may also be used. Cost, operating environment of the motor, intended application and performance all influence the choice. Commutation of a three phase motor with current reversal requires that the windings be switched every 60 electrical degrees. If three sensing devices are spaced 120 electrical degrees, 50% duty cycle, six discrete 3-bit signal states are produced at 60-degree intervals as the rotor turns. Each change of state triggers switching of the stator windings to a particular terminal pair and polarity.

Reversing

The sensors are located so that switching occurs 30 electrical degrees before the peak in the torque vs. angle curve for that terminal pair. Operation of the motor in the reverse direction requires only a change in the switching sequence. A number of manufacturers offer an integrated circuit to perform the sensor signal decoding and provide signals to sequence the power switches for the motor phases.

Brushless Motor Control

DC brushless motors are used in the same types of applications as DC brush-type motors, e.g., servo, constant speed, variable speed, controlled torque, etc. The methods of control are similar to those for brush-type motors. Most will involve some type of current control whether in an open loop mode or a closed loop mode with position and perhaps velocity sensing.

Current Limiting

In current limiting or speed control applications the sensed current may then be compared with a fixed or variable reference and the resulting signal used to control motor current (speed, torque, etc.). Current control schemes include pulse width modulation or linear operation of the power switches. Dynamic braking is accomplished with this circuit by turning off the top switch and turning on the bottom switch in each leg of the bridge. The winding currents are then short circuited through the bottom switches. As DC brushless motor applications have increased, many of these control features have been incorporated into integrated circuit controllers.

DESIGN PROCEDURES (ACCORDING TO YODYIUM TIPSUWAN AND MO-YUEN CHOW)

Procedure 1: Defining Inputs, Outputs And Universe Of Discourse

To apply heuristic knowledge in the FLC, inputs, outputs and universe of discourse are defined first. The inputs are the error (*E*) between the reference (ω_r) and actual speed (ω_a), and the change in error (*CE*). The output is the change in armature voltage (*CU*). The inputs and output illustrated in as shown in Figure 1, are described by:

$$E = e(k) = \omega_r(k) - \omega_a(k) \qquad \textbf{(1)}$$

$$CE = e(k) - e(k-1) \qquad \textbf{(2)}$$

$$CU = u(k) - u(k-1) \qquad \textbf{(3)}$$

Where *k* is the time index.

The maximum range of the DC motor angular velocity that will not damage the motor is +/- 500 rad/s. The possible error in the range is between –1000 rad/s and 1000 rad/s. Therefore, the universe of discourse of *E* is defined to span between –1000 rad/s and +1000 rad/s. The universe of discourse of the change in error is based on the experiment data from the P-I controller design included in procedure 2, which gives the range of error change +/- 5.5 rad/s. For the change in armature voltage, the minimum and maximum defined value are –1.5V and +1.5V respectively [4].

Procedure 2: Defining Fuzzy Membership Functions And Rules

To perform fuzzy computation, the inputs and outputs must be converted from numerical or "crisp" value into linguistic forms. The terms such as "Small" and "Big" are used to quantize the inputs and outputs values to linguistic values. In this paper, the linguistic terms used to represent the input and output values are defined by seven fuzzy variables. Fuzzy membership functions are used as tools to convert crisp values to linguistic terms. A fuzzy membership function can contain several fuzzy sets depending on how many linguistic terms are used. Each fuzzy sets represents one linguistic term. Seven fuzzy sets are obtained by applying the seven linguistic terms. The number for indicating how much a crisp value can be a member in each fuzzy set is called a degree of membership. One crisp value can be converted to be "partly" in many fuzzy sets, but the membership degree in each fuzzy set may be different.

In order to define fuzzy membership function, designers can choose many different shapes based on their preference or experience. The popular shapes are triangular and trapezoidal because these shapes are easy to represent designer's ideas and require low computation time. For performing fine-tuning to improve the efficient of the controller, the adjacent of each fuzzy set value should overlap about 25% [3]. The initial membership functions are illustrated in Figure 2.

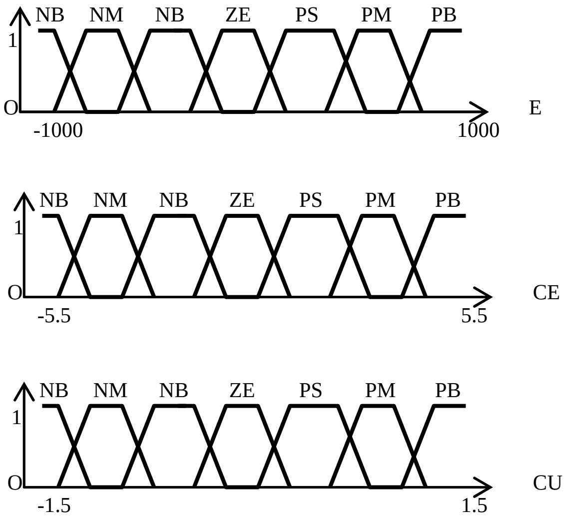


Figure 2: Initial Membership Functions.

Fuzzy rules are in form IF-THEN statements. For example, IF the error (*E*) is equal to positive big (PB) and the change in error (*CE*) is equal to positive medium (PM) THEN the change in armature voltage (*CU*) is negative medium (*NM*). What matters in defining rules are how many rules should be used and how to determined the relation in IF-THEN statements.

Actually, the solutions are based on the experience of an expert or previous knowledge of the system. The critical point is if there is not sufficient knowledge applied in the design, the result could result in negative outcomes. Therefore, in this study, the knowledge from a P-I controller is borrowed first to help to define rules [9]. The velocity transfer function and P-I controller equation are [12]:

$$G_v(S) = W(s)/e_a(s) = K / [JL_aS^2 + (fL_a + JR_a)S + (fR_a + Kk_i)] \quad \textbf{(4)}$$

$$\mu(k) = \mu(k-1) + \left[k_p + \frac{k_iT_a}{2}\right] e(k) + \left[\frac{k_i T_a - k_p}{2}\right] e(k-1) \quad \textbf{(5)}$$

where $K_P = 0.12$ and $K_i = 0.264$

As observed from the P-I control surface, the initial rules are constructed as showed in Table 1. Because the FLC uses the knowledge from the P-I controller, the performance obtaining from the FLC is similar to the P-I controller. The efficiency can be improved by adjusting the membership functions and rules in procedure 3. To determine the armature voltage output, the output in the form of fuzzy sets must be converted to a crisp value. This process is called defuzzification. In this paper, the center of gravity method is chosen. The formula of this method is (equation 6)

Table 1: Fuzzy Rules for DC Motor.

E CE	NB	NM	NS	ZE	PS	PM	PB
PB	NM	NS	NS	NB	PB	PB	PB
PM	NM	NM	NS	NB	PB	PB	PB
PS	NB	NM	NM	ZE	PB	PB	PB
ZE	NB	NB	NM	ZE	PM	PB	PB
NS	NB	NB	NB	ZE	PM	PM	PB
NM	NB	NB	NB	NB	PS	PM	PM
NB	NB	NB	NB	NB	PS	PS	PM

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

$$\mathbf{z} = \frac{\sum_{i=1}^{n} S_iF_i}{\sum_{i=1}^{n} F_i} \quad \textbf{(6)}$$

Where z is the output from defuzzification, S_i is the specific position at the $_i$th fuzzy set, and F_i is the membership degree at the position [5,7].

Procedure 3: adjusting fuzzy membership functions and rules (tuning)

In order to improve the performance of the FLC, the rules and membership functions are adjusted. The membership functions are adjusted by making the area of membership function near ZE region narrower to produce finer control resolution. On the other hands, making the area far from ZE region wider gives faster control response.

Also, the performance can be improved by changing the severity of the rules [8]. After adjusting the membership functions and final membership functions and rules are obtained.

DC MOTOR SPEED CONTROL

A system diagram, Figure 3 provides speed control and regulation for a DC motor. The motor maintains "set point" speed, controlled by a stand-alone converter controller, directed by a BASIC fuzzy logic control program in a personal computer.

The system accomplishes the desired purpose and uses triangles as membership functions to determine the center of mass. The fuzzy control action for the above system is accomplished in a BASIC software program

Rules: Translate the above into plain "linguistic" rules. These Rules will appear in the computer program as "If-Then" statements:

Rule 1. If the motor is running too slow, then speed it up.

Rule 2. If motor speed is about right, then not much change is needed.

Rule 3. If motor speed is to fast, then slow it down.

The next three steps use a charting technique, which will lead to a computer program. The purpose of the computer program is to determine the voltage to send to the speed controlled motor. One function of the charting technique is to determine the "degree of membership" of the “Too slow”, “About right” and “Too fast” membership functions for a given speed. Further, the charting technique helps make the continuous control feedback loop easier to visualize, program and fine tune.

Figure 4 is derived from the previously discussed rules and results in the following regarding voltage to the speed controller:

(a) If speed is “about right” then “**Not** much change” needed in voltage to the speed controller.

(b) If speed is “**Too** slow” then increase voltage to the speed controller to “Speed up”.

(c) If speed is “**Too** fast” then decrease voltage to the speed controller to “Slow down”.

To determine the output, that is, the voltage that will be sent from the controller/signal conditioner/transistor to the speed controlled motor.

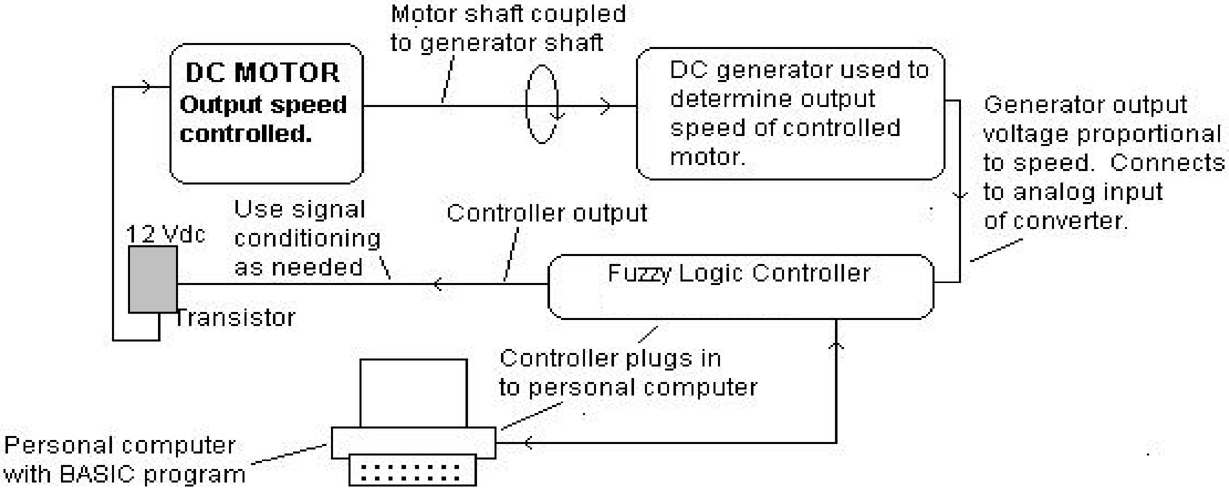


Figure 3: Motor Speed Control Systems [8].

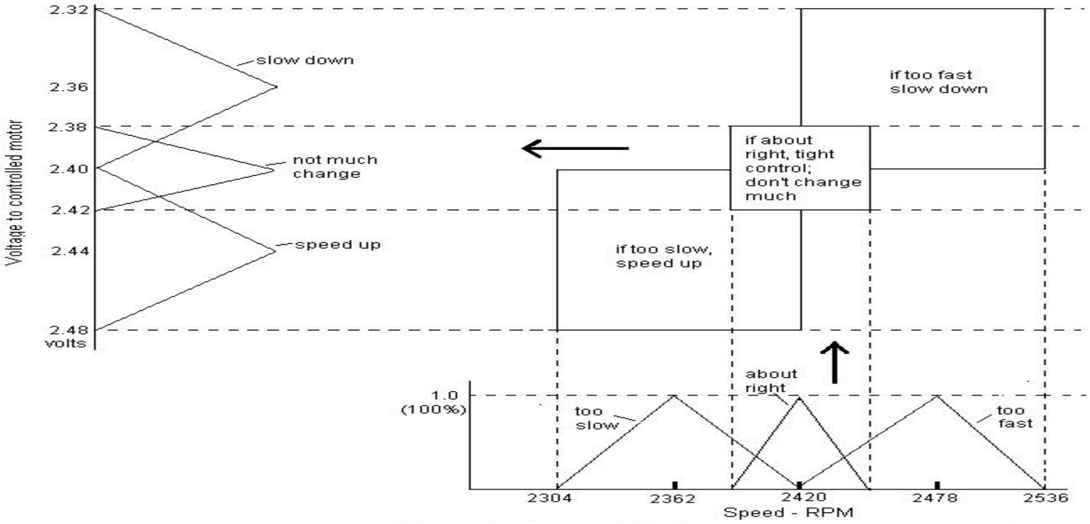


Figure 4: Cause-Effect.

Let us assume that something changes in the system causing the speed to increase from the target speed of 2,420 to 2,437.4 rpm, 17.4 rpm above the 'set point." Action is needed to "pull" the speed back to 2,420 rpm. Intuitively we know we need to reduce the voltage to the motor a little. Motor Speed Control System of Figure 3 could be realized using BASIC programming and the algorithm is shown in Figure 5.

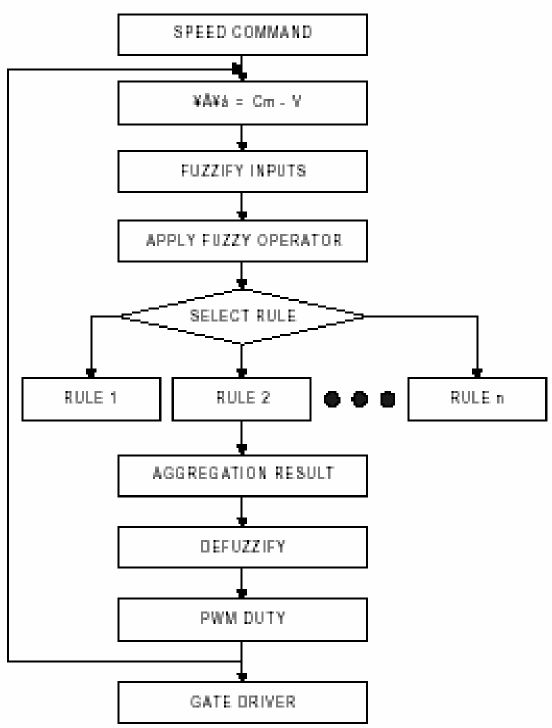


Figure 5: Flow Chat of Fuzzy Reasoning System (Jong-Bae Lee, Tae-Bin Im, et al.).

"The fuzzy logic controller is capable of real time control using fuzzy rule base. The PWM duty ratio for motor control is generated using the fuzzy reasoning algorithm and speed command that was input by speed signal feedback with fuzzy controller".

The fuzzy logic program in the computer directs sending messages to and receiving messages from the controller, thereby directing the measurement and control operation and causing target and actual speed to be displayed. The fuzzy logic controller receives messages from the computer via BASIC language commands. Reply messages to the computer from the fuzzy logic controller are acquired via BASIC. The flow chat of fuzzy reasoning system of Figure 5 explains this procedure.

DC MOTOR SPEED CONTROL SIMULATION

To acquire an accurate fuzzy logic control algorithm, a simulation with the MATLAB® program has been made [11]. A brushless DC Motor is suitable as a servomotor because of its high efficiency and excellent control character. After setting a speed command for 1400 rpm in the program of the target board, a unit step response is measured. Next a constant moment load of 500 g.cm is applied during the operation. The characteristics of a unit step response to no load is shown in Figure 8.

The fuzzy logic controlled DC motor could be used to control the speed of conveyor belts in food frying process. The simulated results are shown in Figures 6 - 9, which are responses to motor startup (no load), motor startup (loaded), the unit step response to no load and the response to constant load (500 g.cm) respectively. In the Figure 8, the rising time to be increased up to 60% of a maximum speed is about 250ms. Also, the characteristics of a response to constant load (500g.cm) while the motor is operating at 1400 rpm is shown in the Figure 9. The characteristic curve to a load variation of motor startup (loaded) is similar to that of motor startup response to no load.

Figure 10 shows the implementation of an FLC for the velocity control of a DC motor by using a fuzzy micro controller incorporated into the design algorithm of the food frying process control system. The controller showed good velocity tracking performance under load and no-load condition, which also established the stability and decoupled nature of conveyor speed control system of industrial food frying process.

As seen from Figure 11, the actual rotor speed overlaps the variable speed reference. The performance of the design controller is evaluated in the presence of load changes. In Figure 12, the speed response under two load variations from 0 to 80 Nm and from 80 to 40 Nm applied at 0.6 sec and 0.8 sec, respectively, is shown.

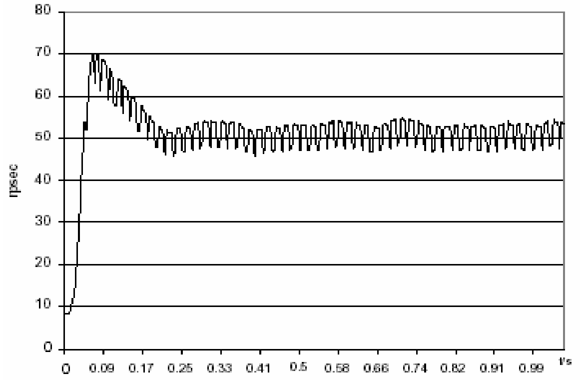


Figure 6: Motor Startup (No Load).

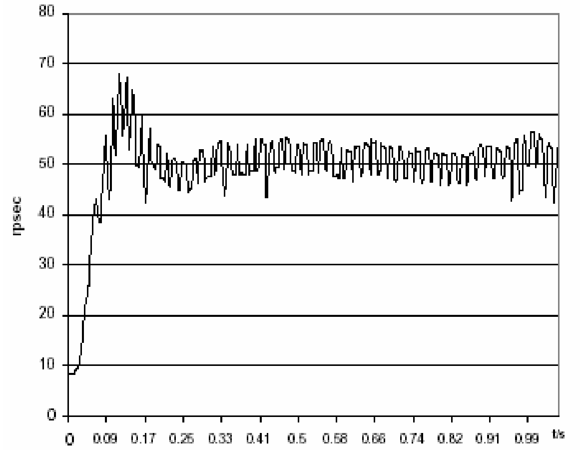


Figure 7: Motor Startup (Loaded).

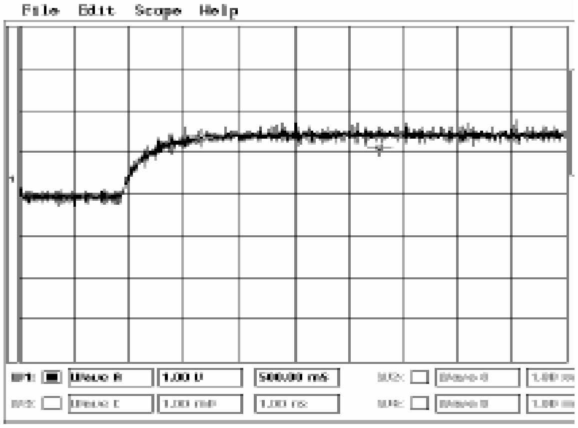


Figure 8: Unit Step Response to No Load.

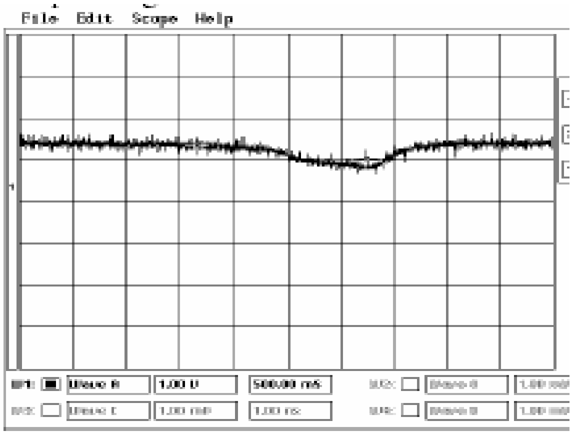
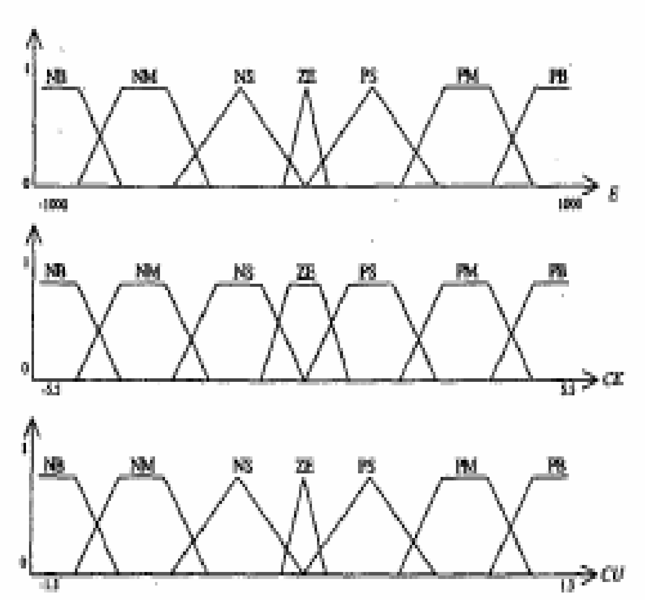


Figure 9: The response to constant load (500g.cm).



(E = Error, CE = Change in Error
and CU = Change in armature Voltage)

Figure 10: Final Membership Functions.

This result demonstrates the ability of the controller to produce the required torque compensating the component in order to maintain a stable response.

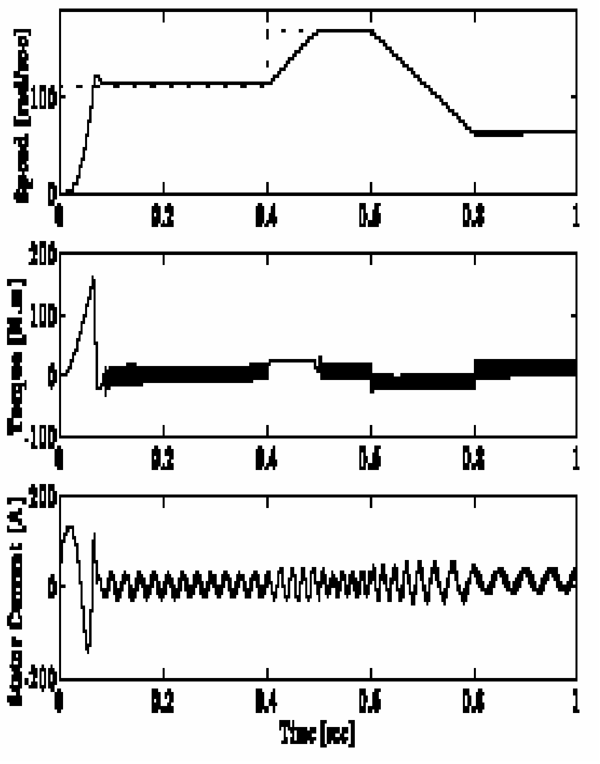


Figure 11: Drive System Responses Under a Variable Speed Reference.

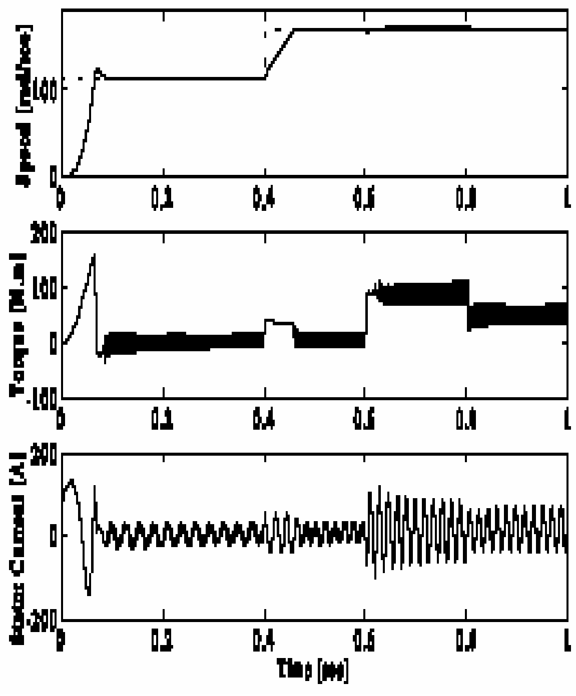


Figure 12: Speed Responses with Two Load Changes

CONCLUSION

In this work, the controller for a brushless DC motor was used which is demanded increasingly when using the fuzzy logic, and this is applied to the speed control of the motor of food frying process equipment. A fuzzy reasoning algorithm is applied to control a brushless DC motor in order to improve the P-I controller, whereby optimum control is difficult to attain under the unstable driving situation of different load conditions. The control accuracy is high and a fast response time resulted.

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APPENDIX

Parts List

(1) IBM or compatible personal computer equipped to run Microsoft Quick BASIC.

(2) 8 channel input; 8 bits, analog/digital converter with 8 on-off, digital output channels and one 8 bit digital/analog output channel.

(3) Signal conditioner (transistor amplifier to adjust levels as needed)

(4) Transistor - 2N3053.

(5) DC motor, 1.5V to 3.0V, 100 ma., 1100 Rpm to 3300 Rpm.

Commutator Characteristics

PARAMETER	VALUE
COMMUTATOR TYPE	HALL-EFFECT SWITCH
INPUT VOLTAGE (Vcc)	4,5 TO 24VDC
PHASING	120^0 ELECTRICAL
OUTPUT TYPE	OPEN COLLECTOR
SINK CURRENT	20ma MAX

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