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Design and PLC Implementation for Speed Control of DC Motor Using Fuzzy Logic

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ABSTRACT

In this article, a speed controller for DC motor is designed and illustrated using fuzzy logic-based programmable logic controller (PLC). The DC motor is an attractive part of electrical equipment in many industrial applications requiring variable speed and load specifications due to its ease of controllability. The designed system is consisted of three main parts including programmable logic controller, pulse width modulation (PWM) bipolar drive and DC motor. In the control section, PLC is used as real time controller and fuzzy logic algorithm is designed based on nonlinear model of DC motor, and its parameters are optimized in MATLAB software. Then, it is implemented using rslogix5000 PLC and programming language ladder for speed control. Finally, with favorable results, the efficacy of the controller is successfully proved under different load conditions. The obtained results demonstrate the efficacy of the PLC intelligent controller in enhancing the accuracy and speed control of DC motor.

1. Introduction

DC motors, as one of the most important electric machines are widely used in various industries, such as electrical systems, control systems and process controls. Therefore, the development of control devices in order to ensure effective efficiency in such systems and making them intelligent is so important. Many control systems for speed control of DC motors have been developed and applied to [1-4]. But in real applications, the process is very complex and it is not easy to define. In this case, intelligent control systems of neural networks and fuzzy logic can be good choices [5-7]. Therefore, in order to improve the speed control system of DC motor and enhance its stability, in this article, fuzzy controller is selected. In references [8-11], the method of speed control of DC motor based on fuzzy controllers has been discussed. However, in most studies, utilizing these control methods is dependeent on PC systems so PLC can provide a possible alternative for the concerns. PLC is widely used to control industrial processes and different environmental conditions [12-18]. Moreover, availability of PLC and its basic features such as mathematical operations and improving graphical user in programming and communications makes it ready to be used in motor speed control systems. Therefore, in this paper, using fuzzy logic method based on PLC, a DC motor speed control system is designed and illustrated.

Figure 1, schematically shows the overall system and process control. In this figure, the input-output analog and digital modules make the connection between the controller algorithm within PLC and the system. Then, the DC motor model, the fuzzy control algorithm, the implementation of fuzzy algorithms in the PLC and the results will be discussed.

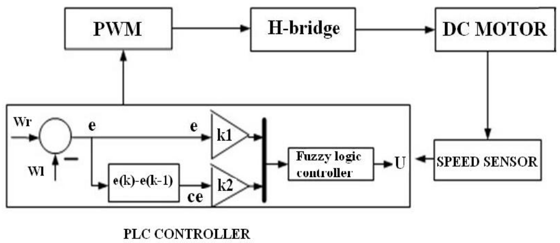

Figure 1: Block diagram of the DC motor speed control system.

2. DC Motor Model

The mathematical model and electrical and mechanical equations of the DC motor, as shown in figure 2, are as follows [19]:

$$V_a = L_a \frac{di_a}{dt} + R_a i_a + e_b \quad (1)$$

$$\phi_m = K_f i_f \quad (2)$$

$$e_b = K_b w_m \quad (3)$$

$$T_m = K_T i_a \quad (4)$$

$$T_m = (J_m + \frac{1}{K_g^2} J_L) \frac{dw_m}{dt} + \frac{1}{K_g^2} b_t w_m \quad (5)$$

So, we have:

$$\frac{w_L(S)}{V_a(S)} = \frac{K_g K_T}{L_a J_{eq} S^2 + PS + R_a b_t + K_g^2 K_T K_b} \quad (6)$$

$$P = L_a b_t + R_a J_{eg} \quad (7)$$

$$J_{eq} = (K_g^2 J_m + J_L) \quad (8)$$

$$K_g = \frac{w_m}{w_L} \quad (9)$$

where V_a is the armature voltage, i_a is armature current, J_m is inertia of the motor, K_b stands for back emf constant, B_m for coefficient of friction, K_T for torque constant, N for gear ratio, J_L for load inertia, and B_L for load friction.

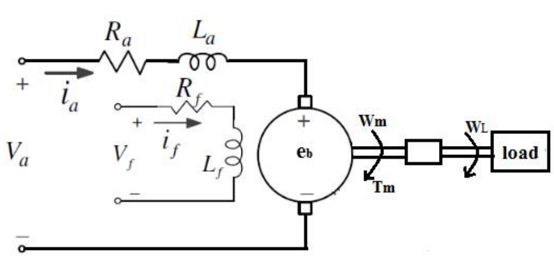

Figure 2: Equivalent circuit of DC motor

Based on the above relationships, various parameters influence each other, leading DC motor speed control systems to be complex, non-linear and multi-variable. Therefore, to improve control system and enhance its stability, based on fuzzy controller, PWM technique is selected to control the DC motor speed proportional to voltage changes. Table 1 shows the parameters of the DC motor.

TABLE 1
PARAMETERS OF MOTOR

Parameters	Values
Rated Power	5 hp
Rated Voltage	240 V
Rated Speed	1750 rpm
Armature Resistance (R_a)	0.78 Ω
Armature Inductance (L_a)	0.016 H
Field Resistance (R_f)	150 Ω
Field Inductance (L_f)	112.5 H
Field-Armature Mutual Inductance (L_{af})	1.234 H
Total Inertia (J)	0.05 kg.m^2
Viscous Friction Coefficient (B_m)	0.01 N.m.s
Coulomb Friction Torque (T_f)	0 N.m

3. FUZZY CONTROLLER

Fuzzy controller is the major part of the control system, which includes fuzzification, rule base and defuzzification [20].

Fuzzification: To perform calculations of fuzzy, the input and output should be converted into the fuzzy variables, the action that is called fuzzification. For fuzzification, it is necessary to determine input, output and their set. Therefore, the error (e) and changes of error (ce) are defined as controller inputs, and signal control u is defined as the output controller. Equations (10) - (11) show how to calculate error (e) and change in error (ce). The numeric domain of {-3, -2, -1, 0, 1, 2, 3} for the inputs e and ce, and numeric domain of {-4.5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 4.5} have been selected for the output u [9].

$$e(k) = w_r - w_L \quad (10)$$

$$ce = e(k) - e(k-1) \quad (11)$$

in which, w_r and w_L are respectively reference speed and actual speed of the motor.

Linguistic values of Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (Z), Negative Small (NS), Negative Medium (NM), Negative Big (NB) are defined as input and output fuzzy sets. Each linguistic value has a membership function of itself. Fuzzy membership functions are tools to convert numeric values into linguistic expressions. Regarding how to use fuzzy statements, a fuzzy membership function can include many fuzzy sets. In this study, considering the simplicity of computation and memory space constraints of PLC, the membership functions of Triangular, smf (S-shaped) and zmf (Z-shaped) are selected. Moreover, depending on the control type, different types of membership functions can be examined and selected. Figures 3 and 4 show the input and output membership functions. Optimization of the parameters of membership functions is done in MATLAB.

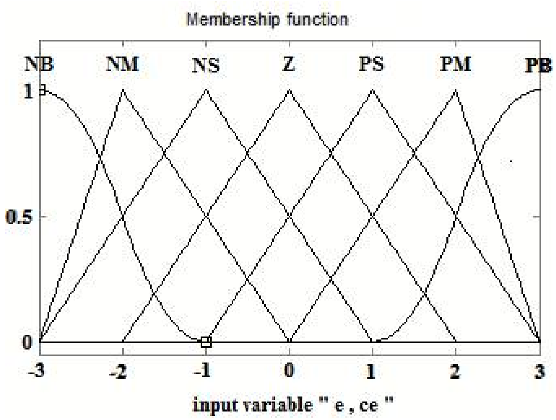

Figure 3: Membership functions of inputs e and ce.

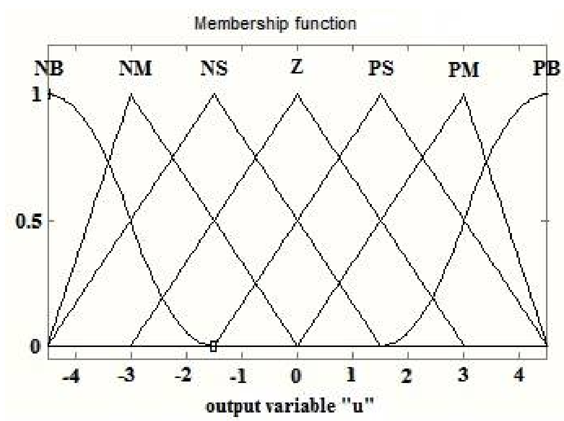

Figure 4: Membership functions of output u.

Rule base: Fuzzy logic controller uses fuzzy rules instead of mathematical formulas and equations for decision-making and control. Rules are often formatted by using “if-then” statements to carry out corrective operation based on the input error or change in error of the system. The number of rules is related to the fuzzy subsets division of the fuzzy variables. Since each fuzzy error and change of error sets have seven linguistic terms, therefore, as shown in table 2, forty-nine fuzzy rules have been selected for DC motor speed control [9]. Two examples of fuzzy rules are defined as follows.

R1: if e is PB and ce is NB then u is Z
R2: if e is NM and ce is Z then u is PM

Defuzzification: Finally, to control DC motor, output must be converted to numerical values by the process that is called defuzzification. In this paper, the weighted average method is used according to equation (12) [19].

TABLE 2
FUZZY LOGIC RULES

U	e						
ce	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PM	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

$$U = \frac{\sum_{i=1}^{n} C_i . \mu(U_i)}{\sum_{i=1}^{n} \mu(U_i)} \qquad (12)$$

In equation (12), $\mu(U_i)$ represents the values of membership functions for output, C_i and shows the values of output MFS centers. Table 3 shows the results of the numerical output of the fuzzy control system after applying the above-mentioned rules and methods.

TABLE 3
THE FUZZY CONTROLLER RULE TABLE

U	e						
Ce	-3	-2	-1	0	1	2	3
-3	4.5	4.12	3.37	2.62	1.5	0.37	0
-2	4.12	3.75	3.15	2.25	1.05	-0.37	-1.12
-1	3.37	3.15	2.55	1.35	0	-1.2	-1.87
0	2.62	2.25	1.35	0.15	-1.2	-2.1	-2.62
1	1.87	1.2	0	-1.2	-2.1	-2.85	-3.37
2	1.12	0	-1.12	-2.25	-2.85	-3.3	-4.12
3	0	-0.75	-2.25	-3	-3.37	-4.12	-4.5

4. IMPLEMENTATION OF FUZZY CONTROLLER IN PLC

In order to use the fuzzy model, the RSLogix 5000 PLC that has an ability to accomplish mathematical processing and has the required programming space is used. To explain the program, all administrative processes within the fuzzy controller should be defined. Therefore, the programming operation in the PLC is comprised of three basic parts: fuzzification, definition of rules and defuzzification [21]. The first step in programming PLC is fuzzification, in which the fuzzy membership functions of the input are defined with respect to the optimization parameters in the fuzzy stage. Figure 5 shows the ladder diagram of PLC program related to the fuzzification of the input error. For input changes of error, depending on the number, domain, and the type of membership function, the steps of figure 5 will be repeated.

The second step is the implementation of the rules of table 2 to calculate the membership degree of fuzzy variable output. For example, the output linguistic variables NB membership degree can be written in PLC as follows:

R1NB=Deg error in PB* Deg ce in PM
R2NB=Deg error in PM* Deg ce in PB
R3NB=Deg error in PB* Deg ce in PB
Deg out NB =R1NB+R2NB+R3NB

For other output fuzzy variables with respect to the number of rules related to them, the program can be written in the form above. The last step of the fuzzy algorithm is the program of defuzzification, which its program is written based on the weighted average method as the follows:

N1= Deg out NB * NB0
N2= Deg out NM * NM0
N3= Deg out NS * NS0
N4= Deg out Z * Z0
N5= Deg out PS * PS0
N6= Deg out PM * PM0
N7= Deg out PB * PB0
N=N1+N2+N3+N4+N5+N6+N7
D=Deg out NB+ Deg out NM+ Deg out NS+Deg out Z+ Deg out PS+ Deg out PM+ Deg out PB
U=output=N/D
Here, PB0= 4.5, PM0= 3, PS0= 1.5, Z0= 0, NS0= - 1.5, NM0 = - 3 and NB0= - 4.5.

Finally, the signal generated by the PLC controller based on the fuzzy algorithm is applied to PWM driver in order to control DC motor speed. In fact, the fuzzy logic system (FLS) generates a value, duty ratio, and passes it to PWM which produces pulses to manage H-bridge.

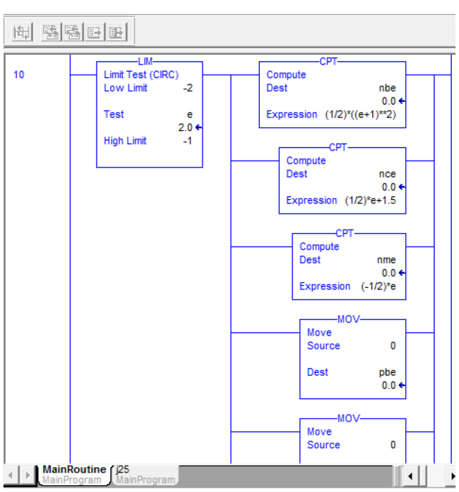

Figure 5: Ladder diagram code generation error of the fuzzification.

5. Results and Discussions

The main parts of the plan include DC motor, PLC controller and PWM driver. PWM driver acts as an interface between DC motor and PLC. PLC is equipped with the digital and analog input-output modules. PLC- based controller provides a signal for PWM driver which is dependent on variables such as error, change in error, and fuzzy rules. We take the e and ce as the antecedent part of the suggested FLS to generate the duty ratio control signal then pass it to PWM for accomplishing fuzzy PWM control signal. The duty ratio is the consequent part of the suggested FLS.

In figure 6, using PLC, the speed control system response curve of DC motor at a speed of 1750 rpm is shown for different load conditions. Table 4 also compares the performance of the controller for the load torque of 50, 30 and 10 N.m respectively.

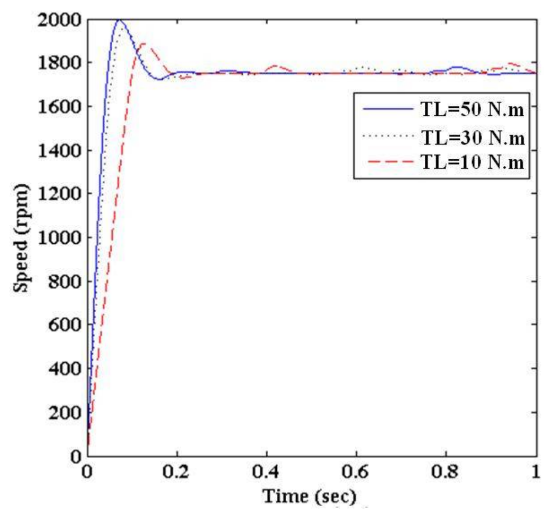

Figure 6: The velocity response curves with TL=50, 30 and 10 N.m

In table 4, the parameters of Tr, Ts, and Os are respectively: rise time, settling time and Overshoot. The results show that the PLC controller can be an appropriate option for speed control of DC motor which is capable of operation under various operating conditions.

Table 4
Performance Comparison

TL (N.m)	Speed : 1750 rpm		
	Tr(sec)	Ts(sec)	Os (%)
10	0.0788	0.098	7.622
30	0.0425	0.173	12.03
50	0.0349	0.163	13.87

6. Conclusions

In this paper, based on fuzzy logic and by using PLC, the intelligent control method of DC motor speed was discussed. Fuzzy control parameters optimized in MATLAB, and then fuzzy control program transferred to rslogix5000. By PWM driver and H-bridge circuit, the controller output signal was applied to the motor. The obtained results proved the effectiveness of the PLC intelligent controller in enhancing the accuracy and speed control of DC motor.

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Biographies

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