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SHORT COMMUNICATION

Multi-input Fuzzy Logic Controller for Brushless dc Motor Drives

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ABSTRACT

The brushless dc motors are used in various applications such as defence, industries, robotics, etc. In these applications, the motor should be precisely controlled to give the desired performance. The proposed controller systems consist of multi-input fuzzy (two-and three-input) logic controller (FLC) and multi-input integrated fuzzy logic controller (IFLC) for the speed control of brushless dc servomotor drive. The input for the controllers are error e(k), change in error [first derivative of error ce(k)] and change of change in error [second derivative of error cce(k)] with a single-output. The error cce(k) is substantial at the overshoots/undershoots and is therefore essential for accurate speed control of brushless dc motor. The error cce(k) has been introduced for the first time in the literature as one of the input in the FLC and IFLC design. The IFLC is designed using FLC and proportional derivation integral (PID) controllers. The controller systems have been studied systematically for the transient and steady-state conditions. The three-input IFLC is found to be superior, more robust, faster, flexible, and is insensitive to the parameter variations as compared with the FLC (with two-and three-input) and conventional two-input IFLC.

Keywords: Fuzzy logic controller, PID controller, brushless dc motor, integrated fuzzy logic controller, second derivative of error

1. INTRODUCTION

The brushless dc motors are gradually replacing dc motors with brushes and ac motors because of their high efficiency and their increasing demand in industrial applications[1]. These motors are extensively used in robotics, computer disk drives, machine tools, electric vehicles and other battery-powered applications[2]. Many varieties of control schemes such as P, proportional integral (PI), proportional derivation integral (PID), adaptive, and fuzzy logic controller (FLCs), have been developed for speed control of brushless dc motors. For the most complex systems, where few numerical data exist and where only ambiguous or imprecise information is available, fuzzy reasoning provides a way to understand the system behaviour by allowing to interpret approximately between the observed input and the output relations[3]. Fuzzy logic, which is based on fuzzy set theory, was first developed by Zadeh[4] in 1965. Control applications such as temperature control, traffic control, dc motor speed control, etc. are the most prevalent of current fuzzy logic applications. Fuzzy logic controllers can be well-suited to control a system with uncertain, complex, inaccurate or nonlinear dynamics. Bay[5], *et al*. proposed a two-input FLC for brushless dc servomotor drive to obtain position and speed control by theoretical simulation and practical design. The results were compared with

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the conventional PI systems and it was concluded that the two-input FLC is superior in performance and is insensitive to the changes in operating conditions. Jong-Bae[6], *et al*. proposed a low-cost speed control system of brushless dc motor using conventional FLC with microcontroller[6]. Ricketts[7], *et al*. proposed a fuzzy logic controller scheme and applied it to high-performance speed and position tracking of brushless dc motors[7]. The results obtained indicated an excellent-tracking performance for both speed and position. The performance of bang-bang controller for comparison sake was also tested and it was found that the FLC performs significantly better than the traditional bang-bang controller.

For special applications, the abovesaid control methods fail to maintain the speed at constant level within a short time. Hence, a need was felt to improve the performance of conventional two-input FLC. For this propose, three-input FLC, two- and three-input IFLC have been designed and developed to give low-settling time and rise time, and also to increase the overall performance of the system. Bassily[8], *et al*. designed a fuzzy proportional-integral controller (FPIC) for brushless dc motor. The FPIC for the speed control of a brushless dc motor was simulated study[8]. Ming-Yuan Shieh, *et al*. designed and implemented IFLC for a dc servomotor system. The IFLC system attempts to control and upgrade existing control systems using fuzzy decision-making logic[9-11]. The main advantage of using the IFLC is that one does not have to redesign an existing control system.

Here, a three-input FLC for the real-time speed control of brushless dc servomotor[12] has been designed and implemented (Model1628T 024B, Faulhaber, Switzerland) using LabVIEW, signal-conditioning extension for instrumentation (SCXI) cards, data acquisition (DAQ) board and fuzzy logic toolkit, all from the National Instruments (NI), USA. A three-input IFLC for the real-time speed control of the said BLDC servomotor has also been designed and implemented. This brushless dc motor so far has not been subjected to control by the above-mentioned hardware, software and multi-input IFLC. The performance of multi-input (two and three) IFLC has been studied for the desired speed. The experimental results have shown remarkable improvement for three-input IFLC over the conventional two-input IFLC and FLC (with two-and three-input) for the speed control of brushless dc servomotor. Also, no experimental report is available on the control of ac/dc motor using IFLC and FLC subjected to three input, i.e., e(k), ce(k), and cce(k). The present experimental research work undertaken is a systematic and comparative study.

2. MULTI-INPUT FLC AND IFLC

For the past several years, the FLCs have been widely and successfully utilised and implemented in numerous industrial applications. A general FLC consists of four modules: A fuzzification module, a fuzzy rule-base, a fuzzy inference engine and a defuzzification module[15]. The interconnections among these modules are shown in Fig. 1(a) for the conventional FLC with two-input. The block diagram of the FLC with three-input is shown in Fig. 1(b). The designed configuration of three-input IFLC is shown in Fig. 2.

A controller compares the process variable (pv) with the set point (sp), determines the error and produces the control signal to minimise the error. The equations for e (k), ce (k), and cce (k) are:

$$e(k) = sp - pv \quad (1)$$

$$ce(k) = e(k) - e(k\text{-}1) \quad (2)$$

$$cce(k) = ce(k) - ce(k\text{-}1) \quad (3)$$

where k is sampling instant of the process.

The FLC produces change in control variable cu (k) which is represented by control action.

$$cu(k) = u(k) - u(k\text{-}1) \quad (4)$$

where u(k) is the present control variable.

The variables e(k), ce(k), cce(k) and cu(k) are the conditions monitored by the FLC. These conditions are expressed in terms of linguistic variables such as negative large (NL), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive large (PL).

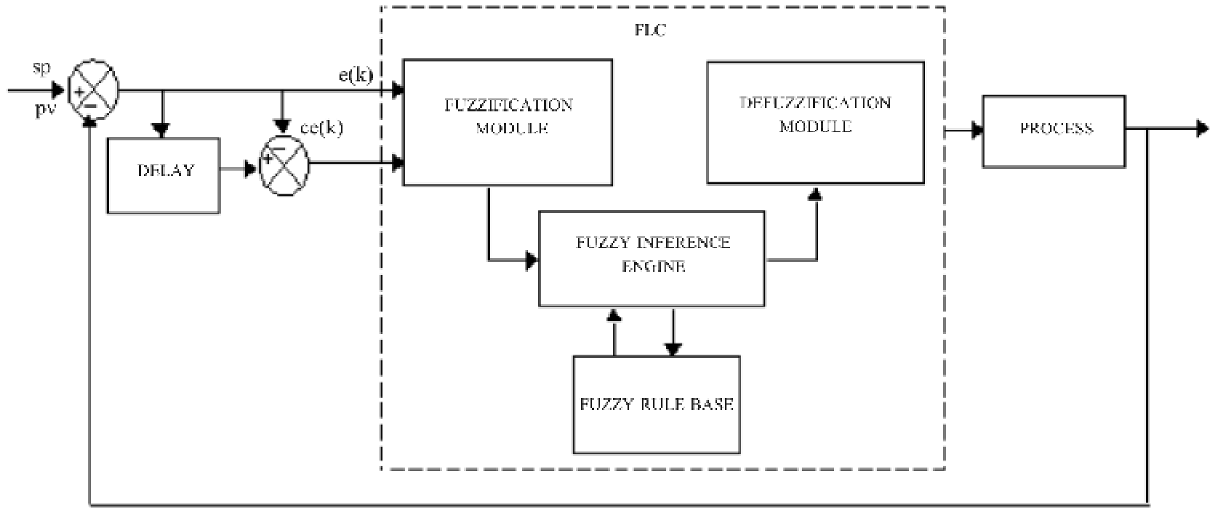

Figure 1(a). Block diagram of fuzzy logic controller with two-input and single-output.

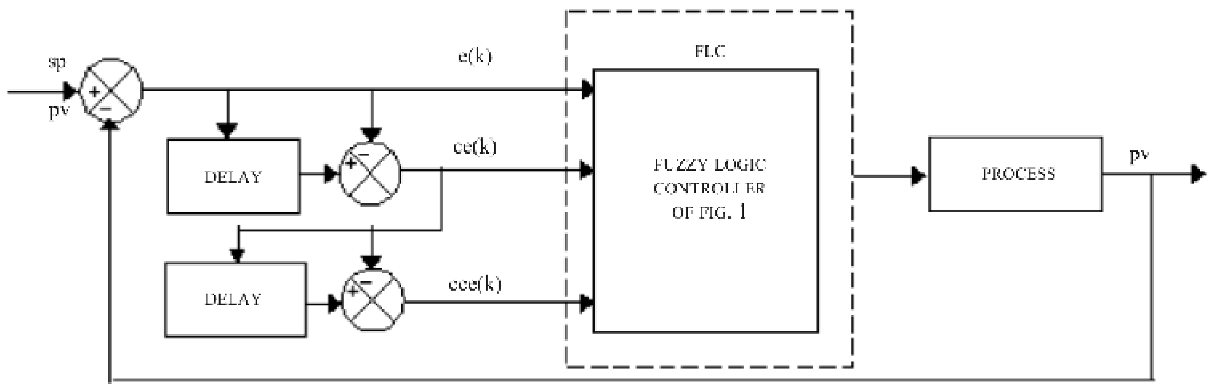

Figure 1(b). Block diagram of fuzzy logic controller with three-input and single-output.

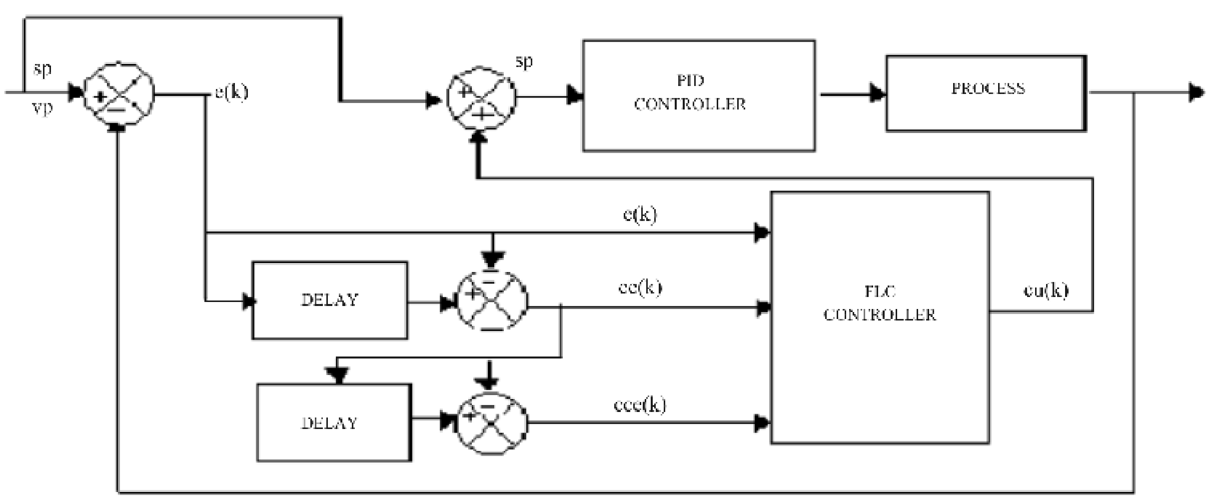

Figure 2. Block diagram of integrated fuzzy logic controller with three-input and single-output.

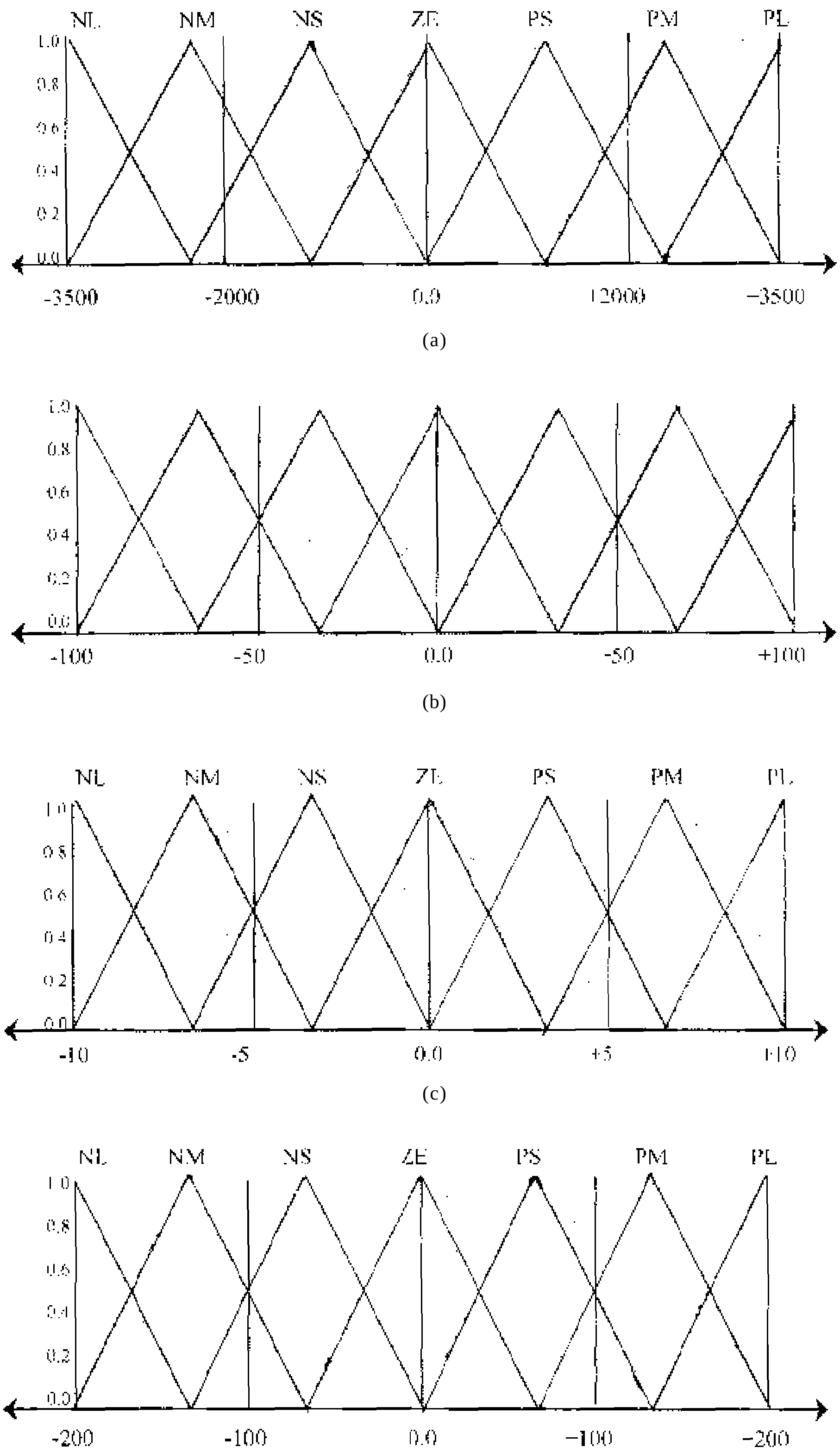

Figure 3. Symmetrical 50 per cent overlapped triangular membership functions for: (a) e(k), (b) ce(k), (c) cce(k), and (d) cu(k). X-axis represents rpm value for different physical variables and Y-axis represents membership function value.

Figure 3 shows the symmetrical triangular membership functions with 50 per cent overlap with neighbouring membership functions for three-input FLC. Depending on these conditions, the rule-base is constructed in the rule-base editor. Depending upon the above conditions, a particular rule (control signal) is fired by the FLC from the rule-base editor. The control signal is in the fuzzified form. To convert this into a crisp form, defuzzification module is used. For two-input FLC, there are $7^2 = 49$ rules. A typical rule is as follows:

IF e(k) is PL and ce(k) is NL, THEN cu(k) is ZE. The rule-base for two-input FLC is shown in Fig. 4

ce/e	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NM	NM	NS	ZE	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PM	PM	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

Figure 4. Rule-base editor for two-input fuzzy logic controller.

For three-input FLC, there are $7^3 = 343$ rules. For want of space, only 40 rules are reproduced in the *Appendix* 1. Some typical rules are:

IF e(k) is PL and ce(k) is PL and cce(k) is PL, THEN cu(k) is PL.

IF e(k) is NL and ce(k) is NL and cce(k) is NL, THEN cu(k) is NL.

The FLC gives out change in control voltage cu (k). This control voltage is converted into present control voltage u(k) using Eqn (4). Many methods are available on defuzzification, however in this application, center of gravity (cg) method is used for defuzzification[16].

The IFLC is a cascade combination of FLC and PID controller. The PID controller output is final control, but it is initially controlled by the FLC.

3. EXPERIMENTAL SETUP

3.1 System Configurations

The block diagram for the speed control of brushless dc motor using FLC is shown in Fig. 5. The brushless dc motor used in the present application has rare earth magnets (SmCo) in its rotor. This

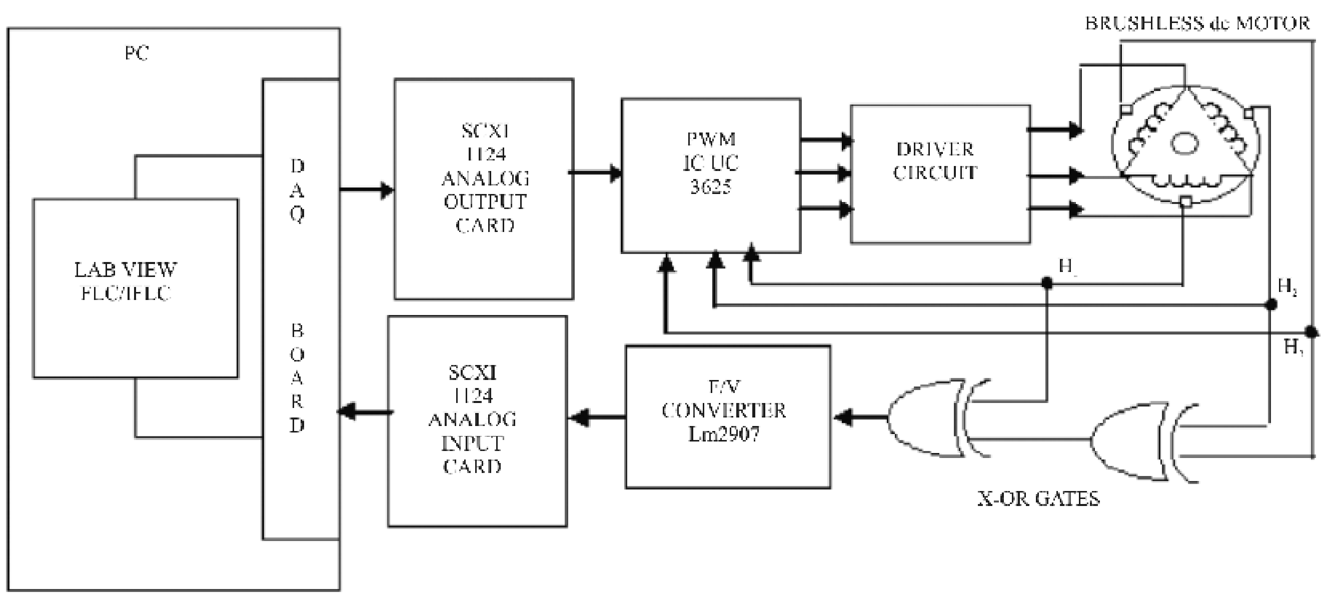

Figure 5. Block diagram of speed control of brushless dc motor using FLC/IFLC.

motor uses a patented unique skew-wound technology developed by the Faulhaber, Switzerland. It offers high acceleration and torque capabilities. This motor has two poles with nominal voltage of 24 V, output power of 11 W, no load speed of 29,200 rpm and no load current of 0.05 A. This motor is a three-phase servomotor with three built-in Hall sensors placed electrically at 120^o apart. The speed of the motor is calculated using the Hall sensor signals. The signals from the Hall sensors are combined using X-OR gates to obtain a train of TTL compatible pulses. These pulses are converted into analog dc voltage using F/V converter (LM2907).

LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. LabVIEW program facilitates virtual instrumentation (VI), which imitates the appearance and operation of physical instruments: VI is defined as a process of combining hardware and software with industry standard computer technology to create a user-defined instrumentation solution. Several other add-on toolsets can be incorporated for developing the specialised applications, the fuzzy logic, and PID toolkits are used in the present application[17-19].

The DAQ board used in the present application consists of analog-to-digital converter, a digital-to-analog converter each with 12-bit resolution, counters and sample and hold circuits[19]. The SCXI cards used in this application are SCXI1122 (analog input card), and SCXI1124 (analog output card). These cards do the job of signal conditioning like amplification, filtering, linearisation, isolation[20], etc.

The voltage from the F/V converter is fed to VI program (in the PC) through SCXI 1122 and DAQ board. The VI program converts this voltage into frequency using the following linear equation:

$$f = a_1 V + a_0 \tag{5}$$

where f is the frequency of the signals from X-OR gates and V is the voltage from the F/V converter; a_1 and a_0 are the slope and intercept drawn from the characteristics of the F/V converter. The obtained frequency is converted into speed using the equation:

$$s = (f^* \ 60\ )/N \text{ rpm} \tag{6}$$

where s is the speed and N is the number of pulses from the Hall sensors per revolution. From the above computations, the measured speed (process variable) is obtained. Using the Eqns [(1)-(3)], e(k), ce(k), and cce(k) are obtained. The e(k), ce(k), and cce(k) are the conditions given as input to the FLC. Depending on these conditions, a particular rule in the rule-base is fired; the FLC gives out the control signal u(k). The obtained control signal is added with + 2.54 V as an offset compensating voltage to drive the PWM controller (IC UC3625). The compensation improves the time-domain response tremendously. The resultant control signal is fed to PWM controller through the DAQ board and SCXI 1124 card. The signals from PWM controller are fed to the transistorised driver circuit, configured as push-pull amplifier. The amplified signals are fed to the armature of the brushless dc motor. The whole cycle or the loop is repeated till the set point (desired value) is achieved. This forms the closed-loop feedback control system for controlling the speed of brushless dc motor.

3.2 Virtual Instrumentation Block Diagram

Figures 6 and 7 show VI block diagrams of the three-input [e(k), ce(k) and cce(k)] FLC and IFLC for the speed control of brushless dc motor, respectively. The output voltage from F/V converter is accessed from SCXI 1122 and DAQ board represented in the form of icon as I/O labelled as Ai input and AI ONE PT, respectively. The accessed voltage is converted into frequency and then into speed using adder and multiplier icons [Eqns (5) and (6) refer]. The process variable is obtained by the above system computations. The transient response is plotted using the waveform chart represented as DBL icon, labelled as speed measurement. The set point is also represented by DBL icon labelled as set point. Here DBL implies double precision floating point value for the input/ output variable.

The variables e(k), ce(k) and cce(k) are obtained using the subtractor and shift register icons. The membership functions and the ranges are chosen using set-editor of fuzzy logic controller design

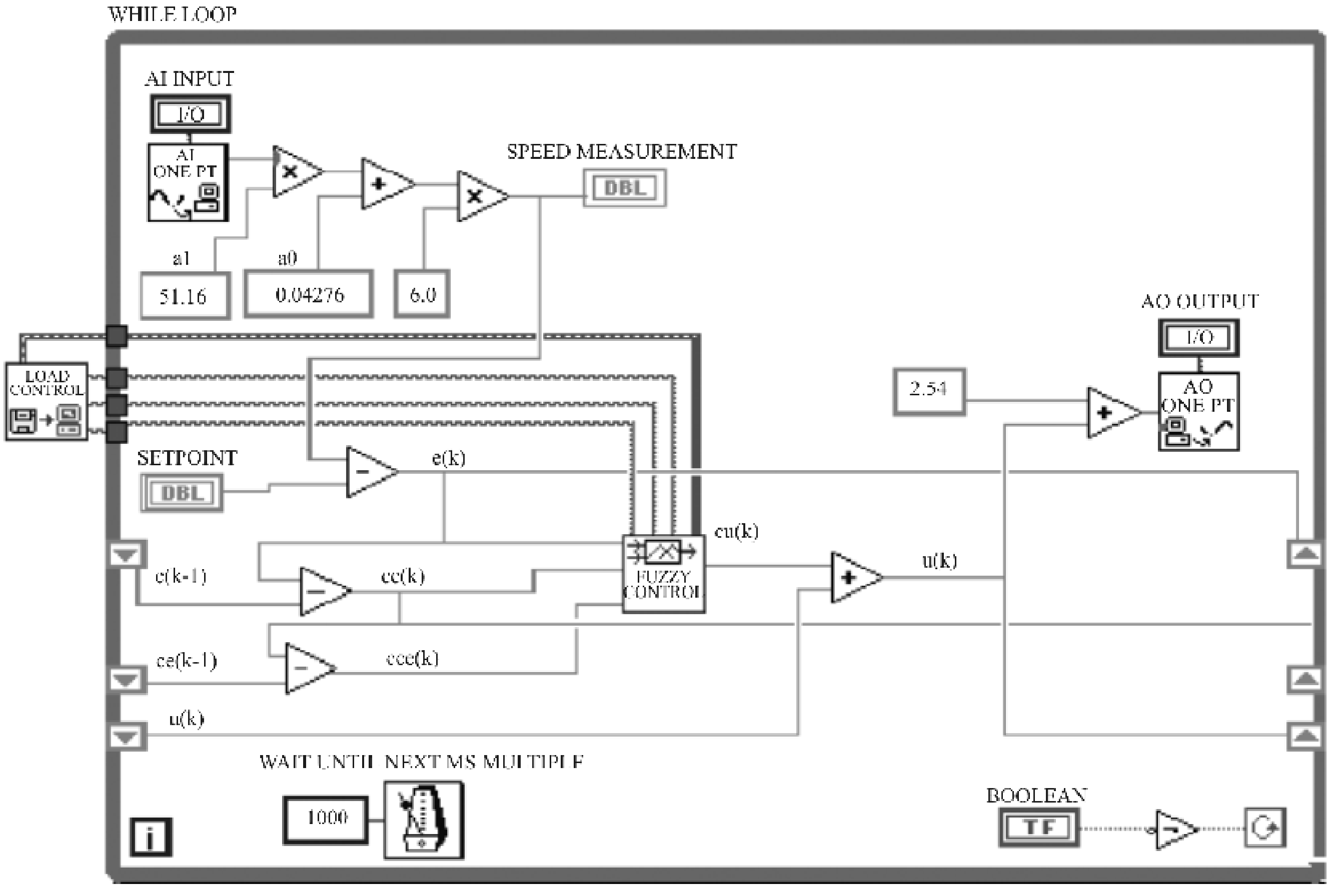

Figure 6. Virtual instrumentation block diagram for speed control of brushless dc motor using three-input FLC.

VI option of fuzzy logic toolkit. The rules and the defuzzification methods are chosen using rule-base editor of fuzzy logic controller design VI option of fuzzy logic toolkit. The designed FLCs consist of 7-number symmetrical 50 per cent overlapped triangular membership functions for fuzzification and center of gravity as defuzzification method. The e(k), ce(k) and cce(k) are selected with the ranges from +3500 to –3500, +100 to –100 and +10 to –10 (Figs 3 and 4), respectively. The range of cu(k) is from + 0.02 to – 0.02 for FLC. The rules and the fuzzification methods are verified using the I/O characteristics in the fuzzy logic controller design in the VI option of fuzzy logic toolkit. The load control icon loads the complete set of fuzzy controller parameters and information defined in the fuzzy control icon such as e(k), ce(k), and cce(k) input variables and cu(k) as control variable.

Defuzzification is the conversion of fuzzy quantity into a crisp quantity, as practical situation needs crisp value for the control action. The FLC gives out change in control voltage cu(k). The present control voltage u(k) is obtained using adder and shift register icons. The control voltage is added with an offset compensating voltage of + 2.54 V for the current sense amplifier (PWM) using adder icon. This control voltage is fed to PWM controller (UC3625) through DAQ board and SCXI1124 analog output card represented as AO ONE PT and I/O labelled as Ao output, respectively. All the above computations are done in the while loop icon labelled as while loop.The Wait Until Next ms Multi-labelled icon is used to control the loop timing, which determines the sampling instant of time[21]. The Boolean icon represented as TF icon and logical NOT icon are connected with the while loop, to control the iteration or period of the cycle of the loop under process.

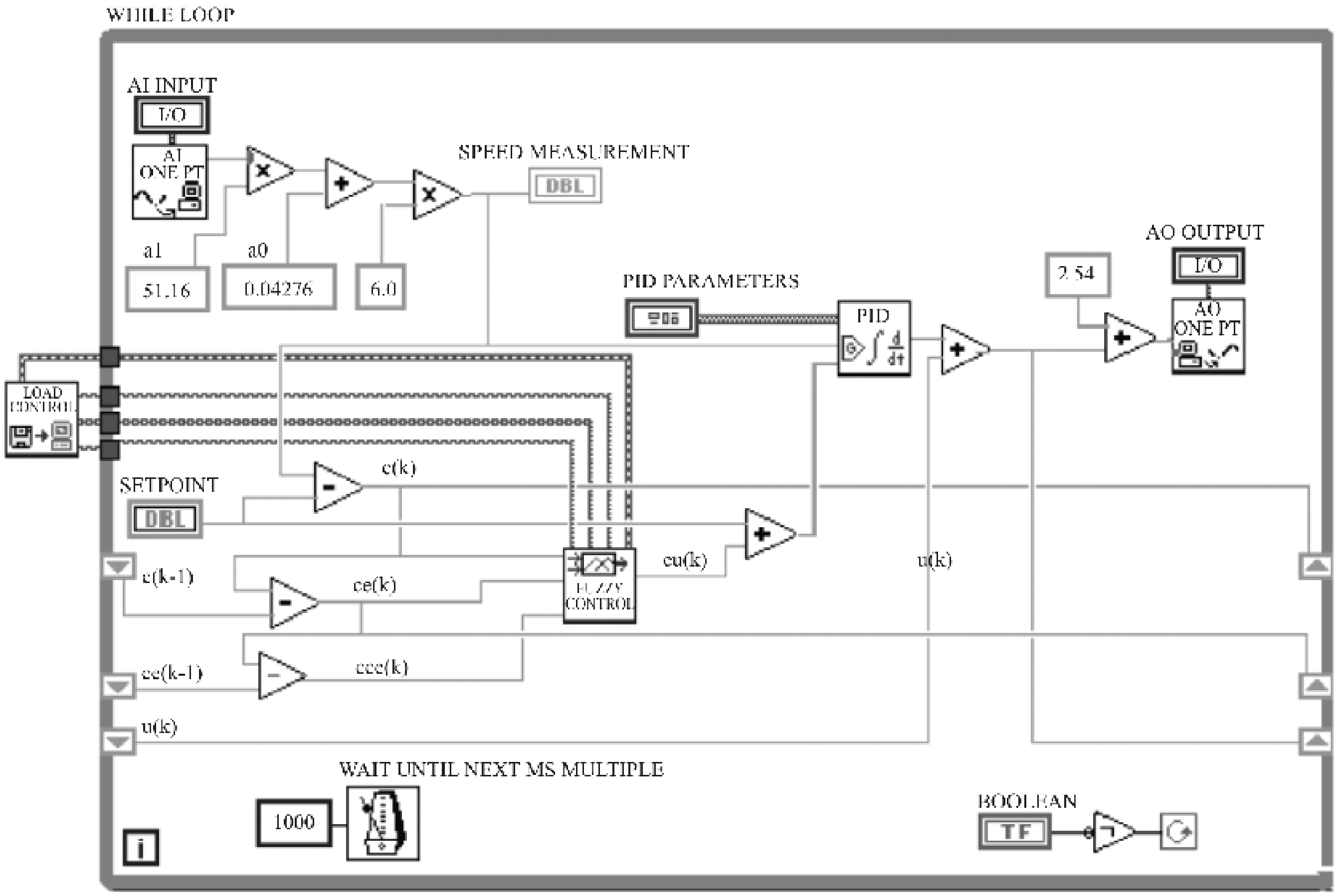

Figure 7. Virtual instrumentation block diagram for speed control of brushless dc motor using three-input IFLC.

For three-input IFLC, the VI block diagram follows the same steps as that of the three-input FLC.

4. RESULTS AND DISCUSSION

The experimental results for the speed control of brushless dc motor are discussed for the desired speed. Figure 8 shows the experimental transient response for the speed control of brushless dc motor using PID, multi-input FLC, and IFLC, respectively for the desired speed of 2500 rpm. For the conventional PID controller, the settling time is 3 s. For two-input FLC, the settling time is 2 s, whereas for three-input FLC is 1.8 s. The IFLC with three-input reduces the settling time to 1.6 s as compared to 1.75 s in the case of two-input IFLC.

In the case of conventional PID controller, the K_p (proportional controller) gives control signal, which varies linearly with error around zero, but it cannot fully eliminate the error to cause perfect steady-state tracking between the set point and the process variable. An integral (I) controller must be added to proportional controller. The PI controller provides good steady state control, but responds sluggishly to transients. This deficiency can be overcome by the addition of derivative (D) element, which constitutes a complete PID controller. The PID controller gives good transient and steady-state control. The tuning of the PID parameters for the speed control of brushless dc motor is time-consuming, as each parameter (K_p, T_i and T_d) have to be varied (monitored) in steps (i.e., one parameter at a time). The deficiencies of the PID controller, if any, can be eliminated by employing FLC in conjunction with the PID controller.

The speed control of brushless dc motor had been carried out using FLC with two-input and

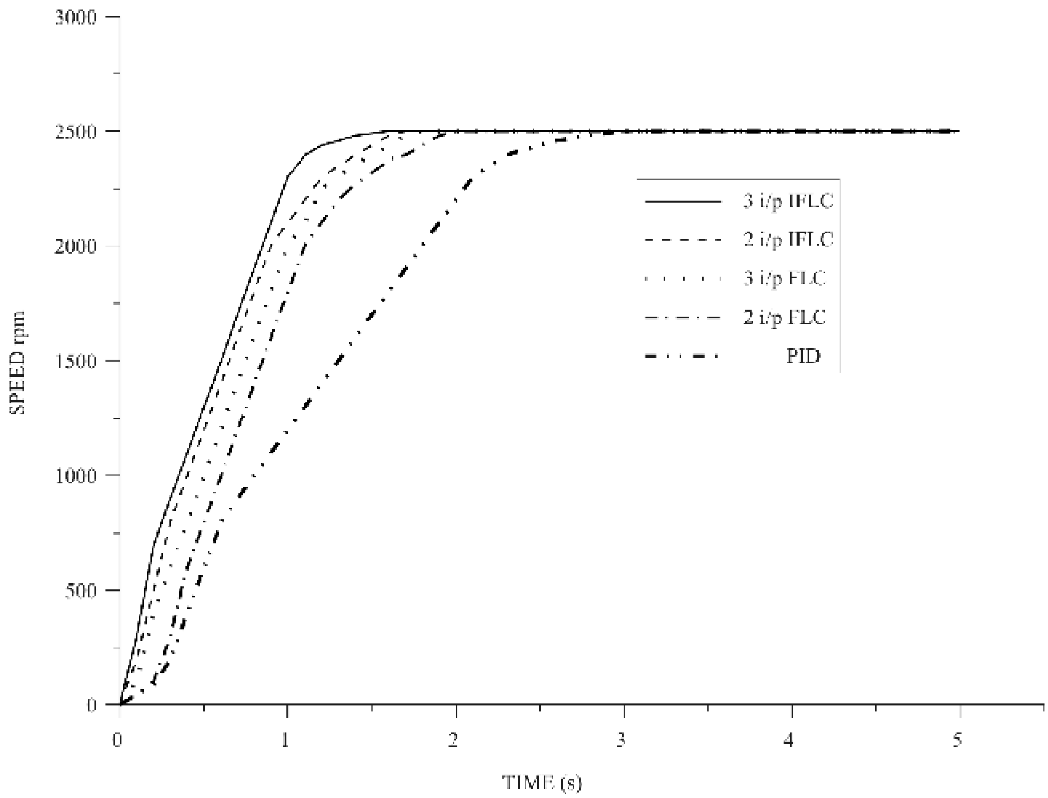

Figure 8. Experimental transient response of conventional PID controller, multi-input (two-and three-input) IFLC, and FLC for brushless dc servomotor drive.

three-input [e(k), ce(k) and cce(k)]. The essence of an FLC is based on a linguistic model (rule-base and the defined membership functions) as opposed to a mathematical model, as in the case with PID controller.

In the fuzzy systems, more than one rule may be fired at the same time, but with varying strengths which lead to a crisp control action through the process of defuzzification. In the case of two-input FLC, there are lower number of rules (49). So even if more than one rule is fired, the strength of the control action will be less accurate. By adding one more input variable that is cce(k), the accuracy of the rules fired by the FLC (three-input) is increased. Introduction of cce(k) in the present control strategy is the first report in the literature.

The ce(k) and cce(k) are zero and appreciable (negative/positive) at the overshoots/undershoots. The inclusion of cce(k) along with e(k), and *ce*(k) as input to the FLC greatly reduces the settling time and steady-state error. The cce (k) is substantial at the overshoots/undershoots and is therefore essential for accurate speed control of brushless dc motor. The control signal in this type of controller gives faster convergence of e(k) and ensures faster settling time, quicker rise time with no overshoots/undershoots, and zero steady-state error.

The two-and three-input IFLC further enhanced the performance of the existing control system, even for variations in motor speed. The control action of the IFLC depends mainly on the change in output signal from the FLC. In the case of IFLC, one does not have to redesign the existing system. By slightly modifying the values of the cu(k) of the FLC, the overall gain of the controller can be adjusted.

6. CONCLUSIONS

The design and development of three-input FLC and IFLC for the speed control of brushless dc motor is being reported for the first time in the literature. Hence one could not compare the results with the others. It is noteworthy that three-input FLC and IFLC give lower settling time than the two-input FLC and IFLC, even though three-input FLC takes larger computational time (because of 343 rules in the rule-base) as compared to the two-input FLC (49 rules in the rule-base). The present system can further be improved by adding one more input variable. Thus, the MISO IFLC with three-input is found to be superior, more robust, faster, flexible, cost-effective, insensitive to the parameter variations, easy to configure and implement as compared with the three-input FLC, two-input IFLC, FLC and conventional PID controller.

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Appendix 1

First 40 Rules Of FLC/IFLC with Three-input and Single-output

Rule No.	IF e(k)	AND ce(k)	AND cce(k)	THEN cu(k)	DoS
1	NL	NL	NL	NL	1
2	NL	NL	NM	NL	1
3	NL	NL	NS	NL	1
4	NL	NL	ZE	NL	1
5	NL	NL	PS	NM	1
6	NL	NL	PM	NS	1
7	NL	NL	PL	ZE	1
8	NL	NM	NL	NL	1
9	NL	NM	NM	NM	1
10	NL	NM	NS	NM	1
11	NL	NM	ZE	NL	1
12	NL	NM	PS	NM	1
13	NL	NM	PM	NS	1
14	NL	NM	PL	ZE	1
15	NL	NS	NL	NL	1
16	NL	NS	NM	NL	1
17	NL	NS	NS	NL	1
18	NL	NS	ZE	NL	1
19	NL	NS	PS	NM	1
20	NL	NS	PM	NS	1
21	NL	NS	PL	ZE	1
22	NL	ZE	NL	NL	1
23	NL	ZE	NM	NL	1
24	NL	ZE	NS	NL	1
25	NL	ZE	ZE	NL	1
26	NL	ZE	PS	NM	1
27	NL	ZE	PM	NS	1
28	NL	ZE	PL	ZE	1
29	NL	PS	NL	NL	1
30	NL	PS	NM	NL	1
31	NL	PS	NS	NM	1
32	NL	PS	ZE	NM	1
33	NL	PS	PS	NS	1
34	NL	PS	PM	ZE	1
35	NL	PS	PL	NS	1
36	NL	PM	NL	NL	1
37	NL	PM	NM	NM	1
38	NL	PM	NS	NS	1
39	NL	PM	ZE	NS	1
40	NL	PM	PS	ZE	1