A comparative study of universal fuzzy logic and PI speed controllers for four switch BLDC motor drive

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Abstract: This paper presents a comparison of PI controller and fuzzy controller for speed control of a low cost brushless DC (BLDC) motor drive used in variable speed drive applications. The cost reduction in BLDC drive system is achieved by the reduction of power semiconductor switches. A PI controller and universal fuzzy controller are designed for the speed control and tested by simulation for various conditions. The simulation is performed by using MATLAB Simulink toolbox and the results show the effective response of the fuzzy controller. The rise time and steady state error of fuzzy controller is improved on an average of about 26% and 55% respectively compared to the conventional PI controller.

Keywords: four switch drive; BLDC motor; switching sequence; PI controller; fuzzy controller.

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1 Introduction

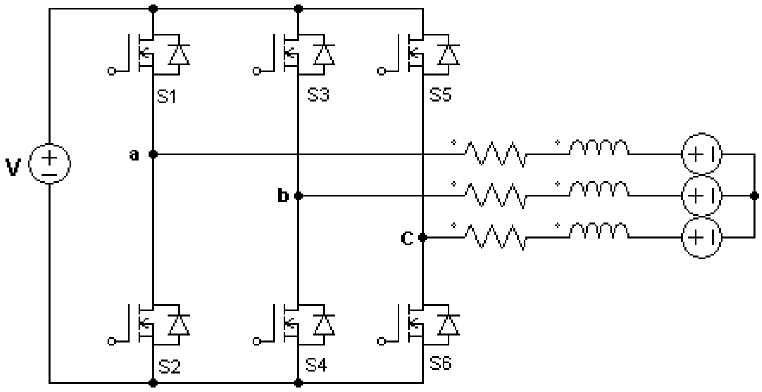
With the advancement of technology and improvement of modern control techniques, the permanent magnet motors are introduced. The permanent magnet motors can be broadly classified into permanent magnet synchronous motor and permanent magnet brushless DC motor (Monfared et al., 2010; Pillay and Freere, 1989; Huang et al., 2012). Conventional DC motors are highly efficient but the primary disadvantage is, need of commutator and brushes which can potentially cause maintenance problems. Due to these reasons, BLDC motors are now-a-days deployed in many fields that are currently fulfilled by brushed motors. When the functions of commutator and brushes are implemented by solid-state electronic drives, maintenance-free motors are realised. These motors are known as BLDC motors and its usage is getting wider now-a-days.

The BLDC motor offers various advantages over brushed DC motors and induction motors like compact construction, reduced weight, low inertia, faster acceleration, high speed, high efficiency, good reliability, long life, low noise, no need of brushes and mechanical commutator, ease in control, no problems related to sparking and no need for frequent maintenance (Bose, 2002).

In this paper, BLDC is preferred over other motors because of its constructive electrical and mechanical characteristics such as high torque to volume ratio, high efficiency and low moment of inertia. BLDC motor finds application in high performance drives such as, robotics, dynamic actuation, machine tools and positioning devices. Due to its enormous advantages it finds its own application in many industrial sectors. Also, another reason to select this motor for study is its cost. Cost and improper electronic commutation pulls down the usage of BLDC motor in various low cost applications (Gokbulut and Tekin, 2006). In topological point of view, the cost of the system can be reduced by reducing the number of power semiconductor switches (Blaabjerg et al., 1997). In order to reduce the switch count, four switch converter topology is adopted. Consequently, one arm in the conventional system as shown in Figure 1 becomes redundant to drive a three phase BLDC motor (Lee et al., 2003). The four switch BLDC motor drive offers various advantages over conventional six switch BLDC motor drive such as

- Reduction of switch device count.
- Reduction of conduction losses.
- Reduced number of interfacing circuits.
- Easier control algorithms to generate logic signals.
- Less chances of destroying the switches.
- Less real-time computational burden (Kim and Lipo, 1996; Lee et al., 2000; Zhu et al., 2016; Hua et al., 2017).

Figure 1 Conventional six switch BLDC motor drive



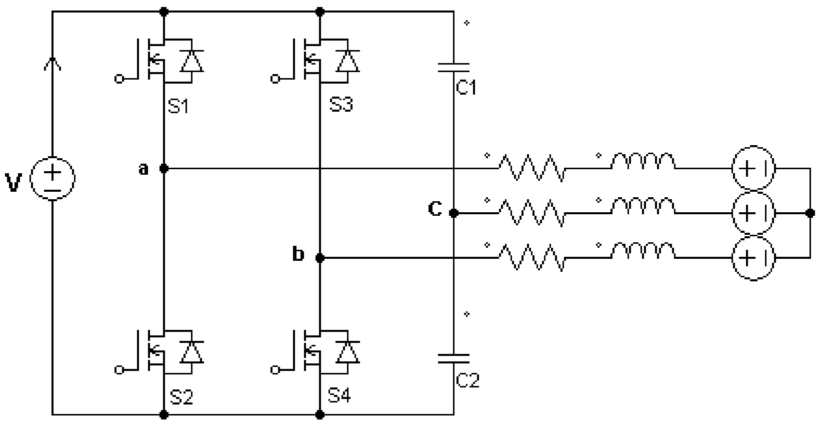
A general method to generate pulse width modulated signals for control of four switch three phase voltage source inverter even there is a voltage oscillations across two DC link capacitors is presented in De Rossiter Correa et al. (2006). In Xia et al. (2009), single neuron adaptive PI algorithm is used for speed regulation. Blaabjerg et al. (1999) proposes an adaptive SVM method to compensate the influence of DC ripple on the output. Also, works based on the position less four switch BLDC motor have been reported in Niasar et al. (2008), Lin et al. (2008) and Su and Mckeever (2004).

Fuzzy logic control is derived from fuzzy set theory. Fuzzy logic controller (FLC) is simple and less intensive to mathematical design. FLC is a best choice in the places where precise mathematical formulations are not possible (Drainkov et al., 1996; Song et al., 2003). The aforementioned researches show the possibility of implementing four switch drive with various control strategies. But, the fuzzy-based performance evaluation of four switch BLDC motor drive was not reported. This work has been materialised by, merging the concept of low cost four switch drive with a simple FLC. It results in robust speed response with reduced cost. Also, the proposed controller design makes it fit for variable drive applications.

2 Four switch drive

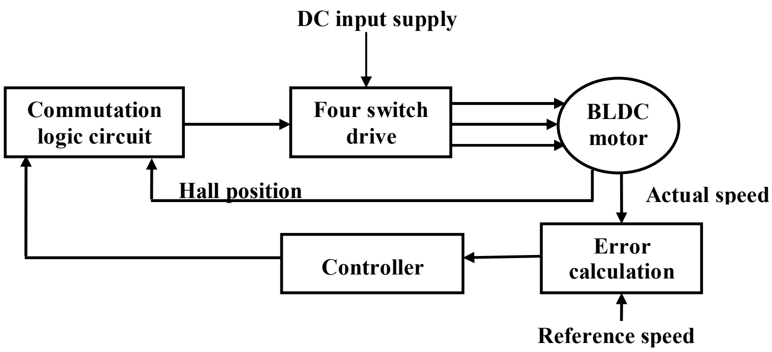
Traditionally, six switch inverters have been widely utilised for variable speed drives. It has various drawbacks such as losses in the six switches, the complexity of the control algorithms and interface circuits to generate six PWM switching signals. The four switch drive has been introduced to overcome these problems.

Figure 2 Four switch BLDC motor drive



The four switch drive is shown in Figure 2. In this four switch BLDC motor drive, the switches of the third arm in the conventional system are replaced by capacitors C_1 and C_2 respectively. Thereby the conduction and switching losses of the corresponding power semiconductor switches can be eliminated. The block diagram of the four switch fed BLDC motor drive is shown in Figure 3. It consists of DC source, four switch inverter, controller, commutation logic circuit and BLDC motor. The Hall position values decide which switch has to be turned ON and turned OFF.

Figure 3 Block diagram of four switch fed BLDC drive



2.1 Principle of operation

Consider the stator coil AB pair and assume that the initial switching pattern is S_1, S_4. According to Faraday's electromagnetic law, the magnetic field of the rotor magnet interacts with induced electro-magnetic field produced by current carrying stator phase coil and as a result of interaction, torque is developed. The developed torque will turn the rotor poles to a new direction and then the rotor poles will face CB pairs of stator coil. At that instant, current is made to pass through the CB pair of the stator coil. Therefore the magnetic rotor interacts with the induced electro-magnetic field and develops torque in the same direction. As a result, the rotor pole advances to a new position. This process continues as per the rotor position. The switches in the commutation circuit conduct for only 120°. Hence the switch utilisation factor is very less.

2.2 Switching signal generation

The speed of the motor is controlled by comparing the actual speed with the reference speed and the error is then fed into the fuzzy controller. Using PWM technique, the gate pulses are generated as shown in Figure 4.

Figure 4 Block diagram of speed control and switching pulse generation

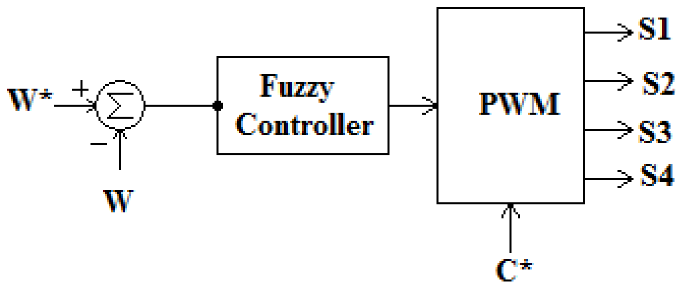


Table 1 Four switch drive switching sequence

Rotor position	*Active phase*	*Conducting switch*
0–60°	A, B	S1, S4
60°–120°	C, B	S4
120°–180°	C, A	S2
180°–240°	B, A	S3, S2
240°–300°	B, C	S3
300°–360°	A, C	S1

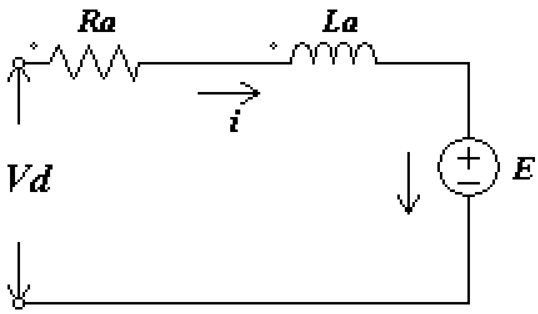
The C^* represents position signals which are produced by the Hall sensors. The S_1, S_2, S_3 and S_4 represent the gating pulses for the corresponding switches respectively. The conduction sequence of the switches is $S_1, S_4 - S_4 - S_2 - S_3, S_2 - S_3 - S_1$. The formulation of switching sequence for the generation of control signal is shown in Table 1. The voltage imbalance is detected by sensing the voltage across two capacitors (V), the compensation signal ΔV is generated. Then, the new control signal V_{cn} is obtained by adding the compensation signal to the control signal V_c. The gate signal is obtained from the comparison of the control signal V_{cn} and the ramp signals in the PWM unit.

3 BLDC motor model

The modelling of the BLDC motor can be developed in the similar manner as that of a three phase synchronous machine but some dynamic characteristics are different. The modelling is based on the following assumptions

- Stator resistances of all windings are equal.
- Self and mutual inductances are constant.
- Iron losses are negligible.
- The magnetic saturation is neglected.
- Power semiconductor devices are ideal.

Figure 5 Typical BLDC motor equivalent electrical characteristics



For simplification phase-A is alone taken under consideration as shown in Figure 5 during the modelling of the BLDC motor. Applying Kirchhoff's voltage law for the equivalent circuit, we get

$$V_d = R_a I_a + L_a \frac{dI_a}{dt} + E \tag{1}$$

where

R_a is the winding resistance

V_d is the terminal voltage

L_a is the equivalent line inductance of the winding

E is the trapezoidal back EMF

I_a is the phase current.

The torque equation for a simple system with inertia J, friction coefficient B and load torque T_l with angular speed of ω_m.

$$T = J\frac{d\omega_m}{dt} + B\omega_m + T_l \tag{2}$$

where $T = K_tI_a$; the torque produced is always proportional to one of the phase current at each time. The transfer function of the BLDC motor obtained is

$$G_i(s) = \frac{\omega_m(s)}{V_d(s)} = \frac{\frac{1}{K_e}}{\tau_e\tau_m s^2 + \tau_m s + 1} \tag{3}$$

where mechanical time constant $\tau_m = (R_aJ/K_eK_t)$ and electrical time constant $\tau_e = L_a/R_a$, K_e is the co-efficient of line back EMF and K_t is the torque constant.

The BLDC motor did not need any complex transformations between the reference frames as compared with the induction motor and synchronous motor. Table 2 lists the parameters extracted from the datasheet of available BLDC motor. Substituting the value we get

$$G_i(s) = \frac{14.993}{1.24e^{-5}s^2 + 10.293e^{-3}s + 1} \tag{4}$$

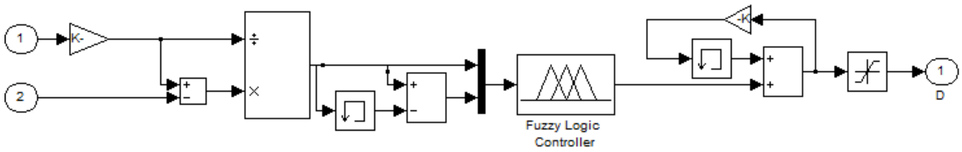
Table 2 Motor parameters

Motor characteristics	*Values (units)*
Terminal resistance, R_a	0.323 Ω
Terminal inductance, L_a	0.389 mH
Voltage constant, K	6.99 V/k rpm
Rotor inertia, J	$0.142e^{-3}$ Kg.m^2
No load speed	3,434 rpm
No load current	1.24 A
Rated power	123 W
Number of poles	8

4 Description of universal fuzzy controller

Traditionally, PI controller is widely used for the control of motor drives because of its simple structure and ease of design. But the main drawback of PI controller is that it does not give satisfactory results when control parameters and loading condition changes rapidly (Varatharaju et al., 2010; Senthil Kumar et al., 2014). The universal FLC will guarantee stable operation, even if there is a change in motor parameters and load disturbances. Fuzzy control is a versatile, effective approach to deal with nonlinear and uncertain system. Mamdani model is used for modelling the fuzzy controller rule base. The error is calculated by determining the difference between the actual speed and the reference speed. The applied voltage should be changed by increasing or decreasing the duty cycle of power semiconductor switches in order to minimise the error. Error (E) and change in error (ΔE) are the inputs for the fuzzy controller whereas the output of the controller is change in duty cycle (D). The structure of fuzzy controller is shown in Figure 6. The steps involved in the fuzzy inference system are given in Figure 6.

Figure 6 Structure of universal FLC



4.1 *Fuzzification*

The process of conversion of numerical variable into a linguistic variable is called fuzzification. In this work seven linguistic variables are used. The linguistic variables are negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB). Triangular membership function is assigned for input and output variables. For the error function, the variables are normalised in the interval [–1.5, 1.5]. The universe of discourse for the change in error function is normalised in the interval [–0.03, 0.03]. Figure 7 shows the input and output membership functions.

4.2 *Inference mechanism*

The linguistic decision rules for the input-output relations are summarised in Table 3. The variables are processed by an inference engine which executes 49 rules (7 × 7). Other inference engines with less number of rules performances are not satisfactory. Thus 7 × 7 rule base is adapted in this article.

4.3 *Defuzzification*

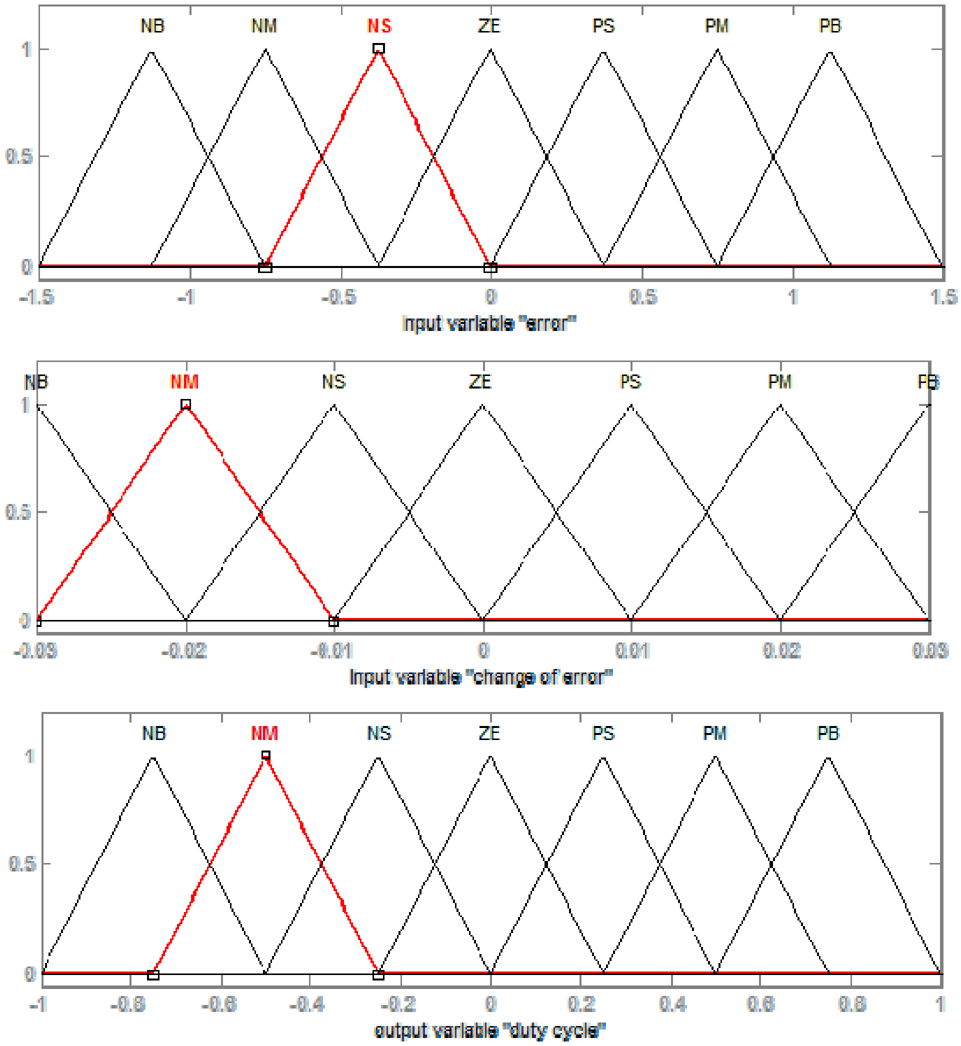
The process of conversion of linguistic variable into a numerical variable is called defuzzification. The centre of gravity (COG) defuzzification technique is used to obtain the crisp output. The equation used for determining the value is given in equation (5)

$$\dot{Z} = \frac{\int \mu(z) z dz}{\int \mu(z) dz} \tag{5}$$

Table 3 Decision table – rule base

E \ *ΔE*	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

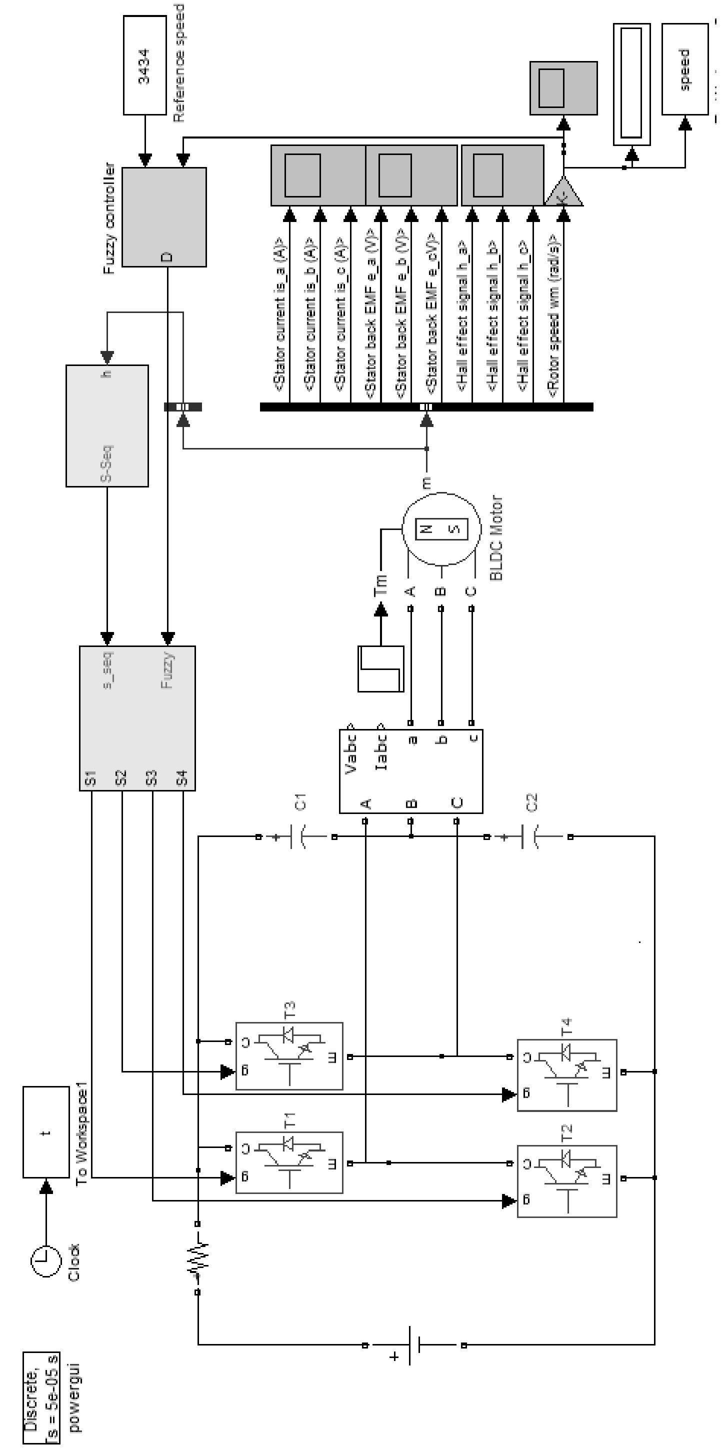
Figure 7 Membership functions of input and output variables (see online version for colours)



5 Simulation results and comparison

To verify the correctness and feasibility of the four switch fed BLDC motor, a complete simulation system was built. The simulation circuit of fuzzy logic and PI controller-based four switch BLDC motor drive is implemented using MATLAB. The simulation circuit of fuzzy logic-based BLDC motor drive is shown in Figure 8.

Figure 8 Simulink model of the system



For PI controller-based four switch fed BLDC motor drive, the fuzzy subsystem is replaced by PI controller. The proportional and integral constant values were designed by Ziegler Nichols PI controller tuning method using the transfer function of the motor. The K_p and K_i values obtained are 0.45 and 73.95 respectively. The switching frequency of 5 kHz is used for pulse generation. Each switch will conduct for 120° and it has 60° non conducting period. The back EMF waveform of the four switch BLDC motor drive is shown in Figure 9. Initially four switch BLDC motor drive is started at no load with a reference speed of 3,434 rpm (rated value) and at the instant 0.25 sec the 50% of the load torque (0.171 N-m) is applied. Between 0.5 to 0.75 sec, the load torque is set as 75% of the rated torque (0.2565 N-m) and at 0.75 sec, the motor is subjected to operate at the rated torque (0.342 N-m).

Figure 9 Back EMF waveform of four switch BLDC motor drive

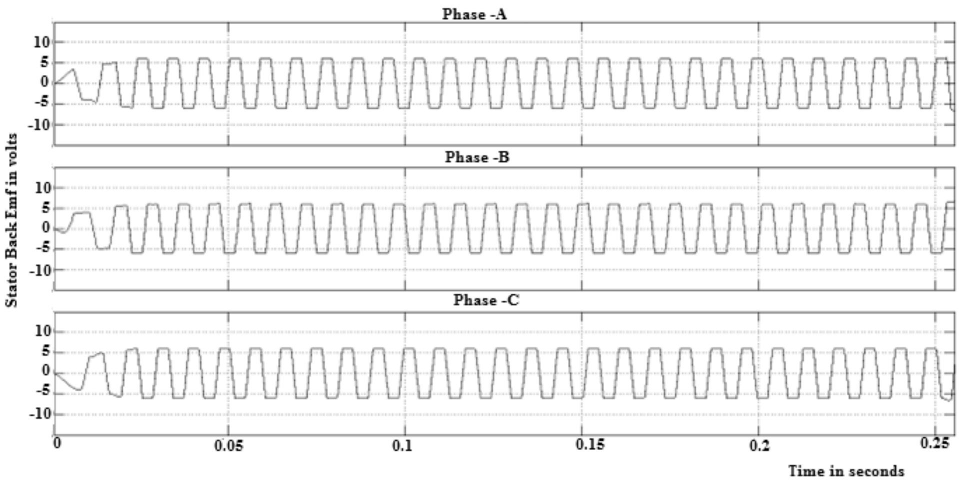
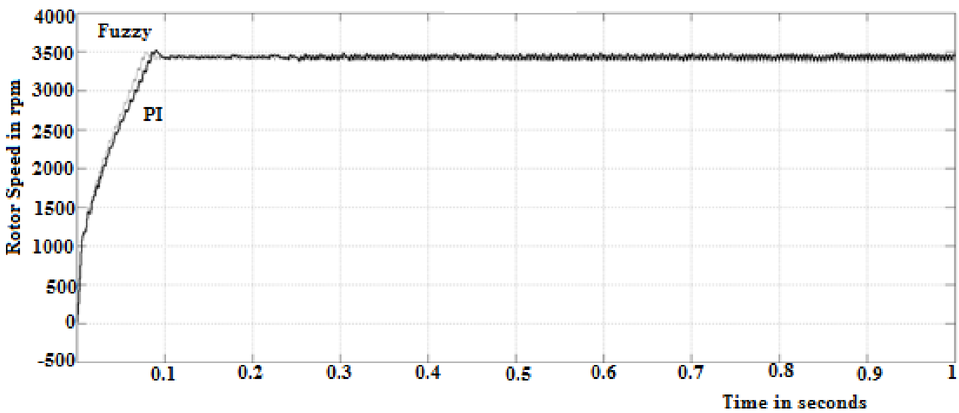


Figure 10 Four switch closed loop speed response for different load torque



The simulated speed response of both controllers for different load conditions is given in Figure 10. From Figure 10 it is evident that for any load torque value, the motor can track the reference speed and the fuzzy controller is more suitable for variable speed applications at varying load conditions. The response of the four switch drive is also examined for different reference speed. Figure 11 depicts the poor performance of fuzzy with 5 × 5 rule base even under half loaded condition. System with 5 × 5 rule base is not able to perform satisfactorily when then there is a sudden dip in reference speed. Figure 12 illustrates the comparative speed response of the fuzzy and PI controller for four switch BLDC motor drive, for different reference speed at rated torque 0.342 N-m. The reference speed of the four switch BLDC motor drive is set initially at 50% of the rated speed (1,717 rpm). At 0.5 sec, the reference speed is increased to 75% of the rated speed (2,565.5 rpm) and during the time interval 1 to 1.75 sec, the rated speed (3,434 rpm) is set as the reference speed. Once again the reference speed is changed to 2,565.5 rpm and 1,717 rpm at 1.75 and 2.25 sec respectively. The response of the system is also observed by changing the control parameters. Figure 13 shows the system response at $J = 0.1e^{-3}$ Kg.m^2 for different reference speed as stated above.

By comparing Figure 12 and Figure 13 it is evident that, fuzzy controller is a universal controller, because inspite of the change in control parameters its performance is better than the PI controller. The results reveal that the four switch BLDC motor drive follows the reference speed with negligible oscillations at both rated torque and rated speed condition. The cost of system mainly depends upon the number of power semiconductor switches used. By reducing the number of switches, the corresponding control circuits can be eliminated. This reduces the complexity of control circuitry design. Hence the four switch BLDC motor drive is cost effective.

Figure 11 Four switch speed response for different reference speed under half load condition and fuzzy having 5 × 5 rule base

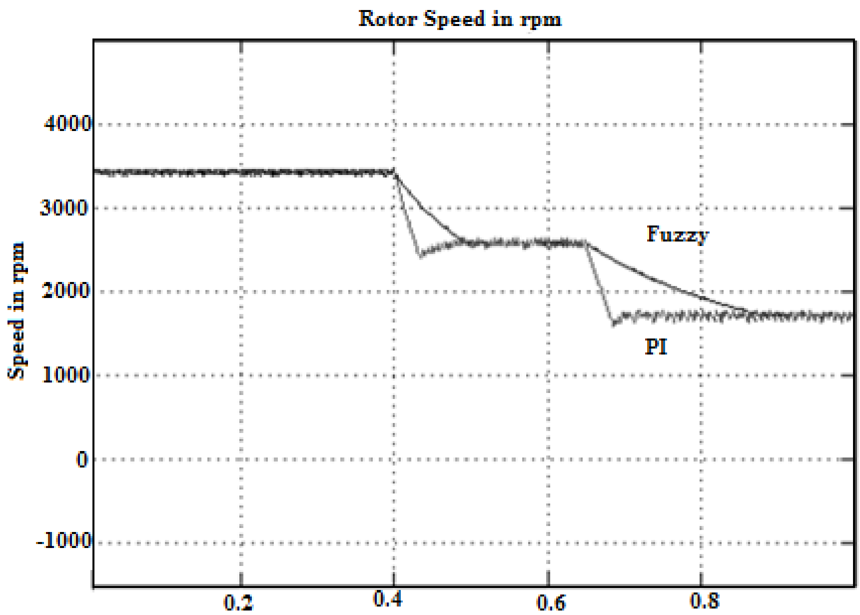


Figure 12 Four switch speed response for different reference speed under rated conditions

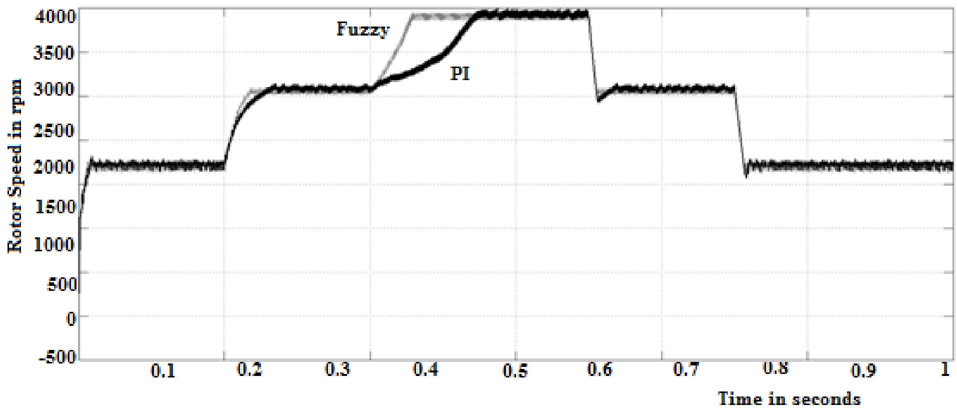


Figure 13 Four switch speed response for different set speed at $J = 0.1e^{-3}$ Kg.m^2

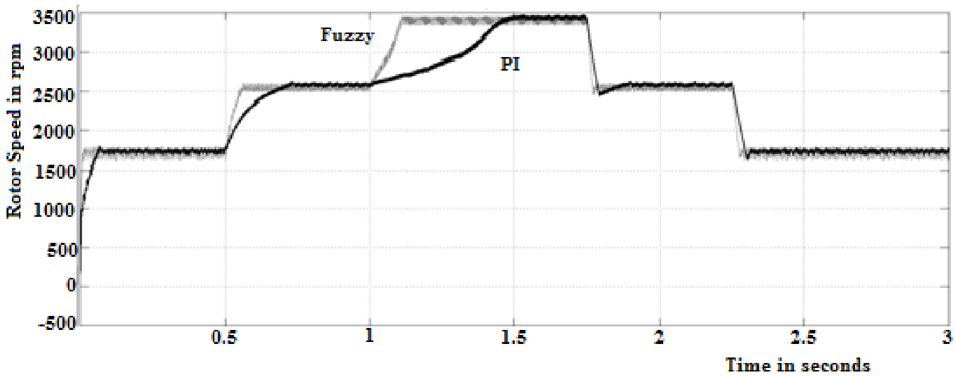


Table 4 Comparison of steady state error in %

Load torque (N-m)	*Reference speed (rpm)*	*PI controller*	*Fuzzy controller*
No load condition	50% of rated speed	0.1	0.05
	75% of rated speed	0.6	0.175
	Rated speed	0.3	0.058
Full load condition	50% of rated speed	0.9	0.86
	75% of rated speed	0.4	0.21
	Rated speed	1	0.23

To evaluate the performance of the universal fuzzy controller-based four switch drive, the results obtained are compared with the results obtained from the PI controller-based four switch drive. Table 4 clearly explains that the error value is very low which mean the tracking speed capability of the system is better even during full load condition. From Table 5 it is evident that during loaded condition the performance of the fuzzy controller is better than the conventional PI controller.

Table 5 Comparison of rise time in secs

Load torque (N-m)	*Reference speed (rpm)*	*PI controller*	*Fuzzy controller*
No load condition	50% of rated speed	0.018	0.0168
	75% of rated speed	0.041	0.036
	Rated speed	0.071	0.064
Full load condition	50% of rated speed	0.07	0.022
	75% of rated speed	0.15	0.14
	Rated speed	0.5	0.223

6 Conclusions

The possibility for low cost and high performance three-phase BLDC motor drive with four switch commutation circuit is realised. The four switch BLDC motor drive system speed tracking capability of is relatively good. The stead state error of the system is within 1%. The closed loop speed control of four switch BLDC motor drive is used in commercial applications with a reduced system cost and it can be employed in variable speed drives under varying load conditions. The rise time and steady state error of universal fuzzy controller is improved on an average of about 26% and 55% respectively than the conventional PI controller. Thus the comparative results have proved that the universal fuzzy controller have a better dynamic performance than that of the conventional PI controller.

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