Performance Estimation of Adaptive Fuzzy Logic Speed Controller for Reduced Switch BLDC Motor Drive

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Abstract
This article deals with the implementation of an adaptive fuzzy logic based reduced switch brushless DC motor drive. In topological view, the cost of the system chiefly depends upon the power semiconductor switches. Hence switch reduction concept is adapted in this paper. The operating principle, switching sequence formulation of reduced switch topology is presented. An intelligent system for reduced switch BLDC drive is designed and tested for different load conditions. Simulation results as well as comparative performance with conventional controllers are presented and discussed. The parameters such as rise time and steady state error are observed. The effectiveness and robustness of the reduced switch BLDC drive for variable speed applications is demonstrated. The rise time and steady state error of the proposed system is improved about an average of nearly 60% and 30% respectively compared to other controllers.

Keywords: BLDC motor, Fuzzy controller, Adaptive fuzzy controller, switching sequence

1. Introduction
Improvement in modern control techniques leads to the design of permanent magnet motors. Even though lot of advantages is there in DC motor, adequate maintenance requirement pulls it back in certain applications. The brushless maintenance-free motors such as BLDC motors gain importance in industrial applications.

The main advantages of BLDC motor over brushed motor are low noise, high reliability, low inertia and high speed. These advantages make BLDC motor to fit in many industrial applications [1-3]. But the drawback of this drive is its cost. The power semiconductor switches used in the commutation circuit is the key factor for high cost. The forth mentioned drawback can be reduced by adapting reduced switch converter topology. It is commonly called as B4 configuration.

Traditional converters, six switches are used in the commutation circuit. In this reduced switch configuration, only four switches and two capacitors are considered. Other advantages of B4 configuration over B6 configuration are less interfacing circuits, control algorithms and computational burden[4,5]. To make the BLDC motor as a best choice for variable speed applications, proper controller design is needed. This article investigates the effective performance of adaptive fuzzy based reduced switch BLDC motor drive for variable speed applications. Also, adaptive fuzzy controller performance is investigated under various loaded conditions. The results of adaptive fuzzy controller are compared with various controllers.
2. Reduced Switch Configuration of BLDC Motor Drive

The topology mentioned in the article, reduces the switch number by four [6-9]. The schematic representation of the proposed reduced switch BLDC motor drive is showcased in Figure 1. The power circuit of this topology consists of four switches with respective anti-parallel diodes and two capacitors. One arm of switches is replaced by two capacitors $C_1$ and $C_2$ respectively. Thereby, the power semiconductor switches conduction and switching losses can be eliminated. The third arm of the commutation circuit is connected to b-phase winding and middle arm of the commutation circuit is connected to c-phase winding. The other arrangements are similar to that of the conventional six switch commutation circuit. The principle of operation is similar to the six switch drive. But there is a difference in the switching sequence formulation, due to the replacement of third arm with capacitors [15-17]. The formulated switching sequence of reduced switch inverter fed BLDC motor drive with reference to hall position $H_a$, $H_b$ and $H_c$ is shown in Table 1.

![Figure 1. Reduced switch BLDC motor drive topology](image)

| $H_a$ | $H_b$ | $H_c$ | Live phases |
|-------|-------|-------|-------------|
| 1     | 0     | 0     | ab          |
| 1     | 0     | 1     | cb          |
| 0     | 0     | 1     | ca          |
| 0     | 1     | 1     | ba          |
| 0     | 1     | 0     | bc          |
| 1     | 1     | 0     | ac          |

The block diagram of closed loop speed control for reduced switch BLDC motor drive is shown in Figure 2. It consists of DC input source, four switch converter, switching circuit, closed loop controller and BLDC motor. The Hall position values decide which switch has to be turned ON and turned OFF.
3. Modeling of BLDC Motor

The BLDC motor equivalent circuit is shown in Figure 3. The modeling is done by assuming equal stator resistance in all three windings and constant losses are negligible [8].

\[ V_a = R_a i_a + L \frac{di_a}{dt} + e_a \quad (1) \]

Where \( R_a \) be the terminal resistance, \( V_a \) be the terminal voltage, \( L \) be the line inductance, \( e_a \) be the trapezoidal back EMF and \( i_a \) be the phase current. The torque equation of the BLDC motor drive is given below,

\[ T = J \frac{\omega_m}{dt} + B \omega_m + T_l \quad (2) \]

where \( T = K_i \omega \) and inertia \( J \), friction coefficient \( B \) and load torque \( T_l \) are the depending parameters of torque. The transfer function of the BLDC motor is

\[ G_i(s) = \frac{\omega_m(s)}{V_d(s)} = \frac{1}{\frac{K_i}{J} s^2 + \frac{B}{J} s + 1} \quad (3) \]
Table 2. Motor Specifications

| Specifications                  | Values     |
|--------------------------------|------------|
| Stator resistance $R_a (\Omega)$ | 0.32       |
| Stator inductance $L_a (mH)$     | 0.39       |
| Voltage constant $K_e (V/k rpm)$ | 6.99       |
| No load Speed (rpm)             | 3434       |
| Current at no load (A)          | 1.24       |
| Rated current (A)               | 7.90       |
| Number of poles                 | 8          |

Substituting the motor specifications of BLDC motor as shown in Table 2, we get

$$G_i(s) = \frac{0.143}{1.24e^{-5}s^2 + 10.293e^{-3} s + 1}$$

4. Design of controller

To meet the requirement of the variable speed drive, an efficient system for regulating the speed of the drive is mandatory. In this paper, three different controllers namely PI, fuzzy and adaptive fuzzy are used for the comparative performance investigation of the reduced switch BLDC drive. The PI controller is the conventional controller and normally preferred controller. The main drawback of the conventional controller is its complex design and it requires complex mathematical models. The gain values of PI controller were designed by using Ziegler Nichols tuning method based on time response and their values are 0.45 and 73.95 respectively. It is found that the performance of the reduced switch brushless DC motor drive with conventional controller is satisfactory in normal no-load condition. But during loading conditions, the controller is not meeting the expectation of variable speed drive[14].

4.1. Fuzzy Logic Controller

During the past several years, fuzzy logic control is applied to a variety of practical problems. The exact mathematical model of the complex systems is not needed in fuzzy system. The main steps involved are Fuzzification, inference mechanism and defuzzification [9-13].

4.2. Design of Adaptive Fuzzy Controller

Adaptive fuzzy controller paves the way to change the fuzzy parameters system based on performance index.
The adaptive fuzzy controller structure is shown in Figure 4. Mamdani type of fuzzy controller with dual input single output is adapted in this article. The syntax of the system is given as below,

\[
\text{if } \Delta E > 0.5 \land \land \Delta E < -0.5 \\
\quad y = \Delta E; \\
\text{else} \\
\quad y = \Delta E \times 2
\]

When \(\Delta E\) value lies in the range -1 to -0.5 and 0.5 to 1, then no adaptation is included in the system. Whereas, when \(\Delta E\) value lies in the range -0.5 to 0.5, scaling factor of 2 is included with the actual value.

### 4.2.1. Fuzzification

In fuzzification numerical variable are converted into a linguistic variable. The linguistic variables used are Negative Big(NEB), Negative Small(NES), Zero(ZE), Positive Small(POS) and Positive Big(POB). Error function the variables are normalized in the interval \([-2, 2]\) for error and change in error functions in the interval \([-0.02, 0.02]\). The membership graphs of input and output are shown in Figure 5.

### 4.2.2. Inference Mechanism

Fuzzy control rules are obtained from the analysis of the system behavior. The inference engine processes the variables which executes 25 rules (5x5).

| E AE | NEB | NES | ZE | POS | POB |
|------|-----|-----|----|-----|-----|
| NEB  | NEB | NES | ZE | POS | POB |
| NES  | NEB | NES | ZE | POS | POB |
| ZE   | NEB | NES | ZE | POS | POB |
| POS  | NES | ZE  | POS| POB | POB |
| POB  | ZE  | POS | POB| POB | POB |
4.2.3. Defuzzification

Defuzzification is the method by which linguistic variables are transferred into numerical variables. The center of gravity (COG) method is used in defuzzification. The equation used for determining the value is given below

$$\hat{Z} = \frac{\int \mu(z)dz}{\int \mu(z)dz}$$

(5)
5. Simulation Study

Simulation has been conducted for the speed control using adaptive fuzzy controller. It is carried by using the MATLAB software with the specifications mentioned in Table 2. The simulation circuit of the proposed system is shown in Figure 6.

There are three Hall sensors, which determine the rotor position and output from the Hall sensors are binary as depicted in Figure 7. The 5 kHz switching frequency is used and each switch will be in conduction for a period of 120°. The trapezoidal back EMF waveform of a reduced switch brushless DC motor drive is shown in Figure 7. The speed response of the proposed system for different reference speed at rated torque is shown in Figure 9. (a), (b).
Figure 8. Back EMF waveform

Figure 9. (a), (b) Closed loop speed response of proposed system with different reference speeds
Table 4. Rise time (seconds) comparison

| Load torque (N-m) | Set Speed (rpm) | PI controller | Fuzzy controller | Adaptive Fuzzy controller |
|------------------|-----------------|---------------|-----------------|--------------------------|
| Full Load Condition | 1717 | 0.07 | 0.022 | 0.018 |
|                  | 2575.5 | 0.15 | 0.14 | 0.06 |
|                  | 3434(rated) | 0.5 | 0.223 | 0.154 |

From the response, it is clearly evident that performance of the system is better even under rated load condition. The results obtained are compared with PI controller, fuzzy based four switch BLDC motor drive and the observed results are listed in Table 4 and Table 5.

Table 5. Steady state error (%) comparison

| Load torque (N-m) | Set Speed (rpm) | PI controller | Fuzzy controller | Adaptive Fuzzy controller |
|------------------|-----------------|---------------|-----------------|--------------------------|
| Full Load Condition | 1717 | 0.9 | 0.86 | 0.46 |
|                  | 2575.5 | 0.4 | 0.21 | 0.09 |
|                  | 3434(rated) | 1 | 0.23 | 0.2 |

6. Conclusion

This paper presents results of extensive comparative studies, related to PI, fuzzy and adaptive fuzzy controller for reduced switch BLDC motor drive. Compared to conventional controllers, improved performance is observed in adaptive fuzzy controller for reduced switch BLDC motor drive. The steady state error of adaptive fuzzy controller is 66.753% times better than PI and 30.0153% times better than fuzzy controller. Whereas the rise time of adaptive controller is 67.82%, 35.4221% times superior than PI, fuzzy controllers. This shows, the proposed system is suitable for many variable speeds applications even under varying loaded conditions.

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