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Simulation and Analysis of Intelligent FLC for BLDC Drive

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Abstract:
This paper presents the performance of the Brushless DC Motor (BLDC) using Intelligent Fuzzy Logic Controller. The mathematical model of BLDC drive is proposed. Usually fuzzy logic controllers are poor under load disturbances and transient conditions. To enhance the dynamic performance of the BLDC drive, a novel implementation of speed controller based on modified fuzzy logic control is presented which is termed as Intelligent FLC. A complete simulation of closed loop BLDC drive using Intelligent FLC is simulated successfully using MATLAB / Simulink. The entire BLDC model simulation is divided into the several independent functional modules such as BLDC module, current control module, PWM module inverter module and so on. The simulation model of the BLDC Drive simulation can be obtained by combining these modules. In order to verify the effectiveness of the Intelligent FLC, the simulation results are compared with other controller (PI and FPI controller). The simulation result shows Intelligent FLC has superior performance than PI and FPI controller.

Key words*: BLDC, FLC, PI, FPI, Fuzzy tuned PI*

1. Introduction

In variable-speed control of AC motor drives, utilization of BLDC motor has been widely used because it has a simpler structure and lower cost than the other AC motors**.** BLDC motor also known as electronically commutated motors (ECMs, EC motors) are synchronous motors which are powered by a DC electric source via an integrated inverter, which produces an AC electric signal to drive the motor; additional sensors and electronics control the inverter output. The motor part of a brushless motor is often a permanent magnet synchronous motor, but can also be a switched reluctance motor, or induction motor.

Many machine design and control schemes have been developed to improve the performance of BLDC motor drives. The model of motor drives has to be known in order to implement an effective control in simulation. Analysis of fuzzy logic controlled brushless DC motor drives using MATLAB/Simulink. Initially a fuzzy logic controller is developed usingMATLAB Fuzzy-Logic Toolbox and then inserted into the Simulink model.The control algorithms, fuzzy logic and PI are compared. The PWM signals are generated by comparing the Hall sensor feedback signals and the motor current. The entire BLDC is control simulation divided into several independent functional modules such as

BLDC module, current control module, PWM module inverter module and so on. The simulation model of the BLDC Drive simulation can be obtained by combining these modules.

Typical Hall-sensor controlled VSI driven BLDC motors, where the inverter operates using 120-Degree commutation method. Rotor position is sensed by Hall Effect sensors embedded into the stator which gives the sequence of phases. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high/low signal, indicating the N or S pole is passing near the sensors. The sensorless mode of control is highly advantageous if the motor is operating in dusty or oily environments, where occasional cleaning of Hall sensors is required for proper sensing of rotor position. Further, if the motor rating is very low, the power consumption of the position sensors can substantially reduce the motor efficiency and in compact units such as computer hard disk drives it may not be possible to accommodate position sensors.

2. The Mathematical Model of BLDC

The flux distribution in BLDC motor is trapezoidal and therefore the d-q rotor reference frames model is not applicable. Given the non-sinusoidal flux distribution, it is sensible to derive a model of the permanent magnet BLDC in phase variables.

The derivation of this model is based on the assumptions that the induced currents in the rotor due to stator harmonic fields are neglected and iron and stray losses are also neglected. The motor is considered to have three phases even though for any number of phases the derivation procedure is valid.

Modeling of the BLDC motor is done using classical modeling equations and hence the motor model is highly flexible. These equations are described based on the dynamic equivalent circuit of BLDC motor. For modeling and simulation purpose assumptions made are the common star connection of stator windings, three phase balanced system and uniform air gap. The mutual inductance between the stator phase windings are negligible when compared to the self inductance and so neglected in designing the model. Modeling equations involve,

Dynamic model equation of motion of the motor,

$W_m = (T_e - T_l) / Js + B$ (1)

T_e = electromagnetic torque,

T_l = load torque,

J = moment of inertia,

B = friction constant

Rotor displacement can be found out as,

$\Theta_r = (P/2)\, W_m / s$ (2)

P = Number of poles

Back EMF will be of the form,

$E_{as} = k_b f_{as} (\Theta_r) W_m$ (3)

$E_{bs} = k_b f_{bs} (\Theta_r) W_m$ (4)

$E_{cs} = k_b f_{cs} (\Theta_r) W_m$ (5)

K_b = back EMF constant

Stator phase currents are estimated as,

$i_a = (V_{as} - E_{as}) / (R+Ls)$ (6)

$i_b = (V_{bs} - E_{bs}) / (R+Ls)$ (7)

$i_c = (V_{cs} - E_{cs}) / (R+Ls)$ (8)

R = resistance per phase,

L = inductance per phase

Electromagnetic torque developed,

$T_e = (E_{as} i_{as} + E_{bs} i_{bs} + E_{cs} i_{cs}) / W_m$ (9)

3. Intelligent Fuzzy Logic Controller

The Intelligent FLC is designed to replace the Fuzzy PI controller, which shows in Figure. 1. and Figure.2 shows a simulation diagram of Intelligent FLC

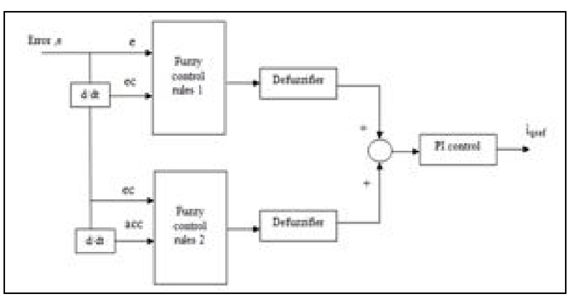


Figure 1: Block Diagram of Modified Fuzzy Tuned PI Controller

The Intelligent FLC uses only two inputs, speed error (e) and rate of change of speed error (ec). But in this model an additional input named 'accelerated rate of change of error' (acc) is used to improve the transient response of the system. With these three inputs, the structure of the FLC is composed of two independent parallel fuzzy control blocks, each of which contains the corresponding fuzzy control rules and a defuzzifier. The incremental output of the FLC is formed by algebraically adding the outputs of the two fuzzy control blocks.

The fuzzy inference of Intelligent FLC is based on the fuzzy rule table set previously. So the algorithm of fuzzy inference is not complex. The parameters of PI can be adjusted on-line, which can be changed through the inquiry to fuzzy control rules table saved a forehand in the computer.

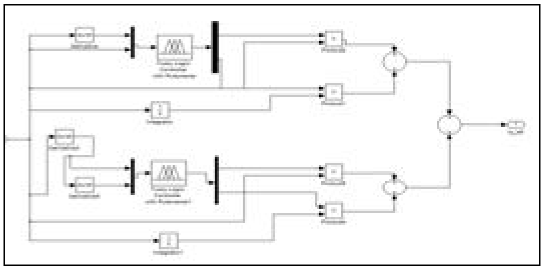


Figure 2: Simulation of modified Fuzzy Tuned PI controller

The calculated speed of the controller is very quick, which can satisfy the rapid need of the controlled object. The control algorithm of traditional PI controller can be described as,

$u(k) = k_P e(k) + k_I \int e(k)$ (10)

Where, k_P is the proportional gain, k_I is the integral gain and e (k) is the speed error.

The design algorithm of Fuzzy PI controller in this paper is to adjust the k_p and k_i parameters online through fuzzy inference based on the speed error (e) and rate of change of speed error (ec) to make the control object attain the good dynamic and static performances.

3.1. The Input Variables and Output Variables

Speed error (e) and rate of change of speed error (ec) are used as fuzzy input and the proportional constant $k_{P,}$ the integral constant k_I are the fuzzy output and Figure.3 shows Fuzzy tool box which has input and output.

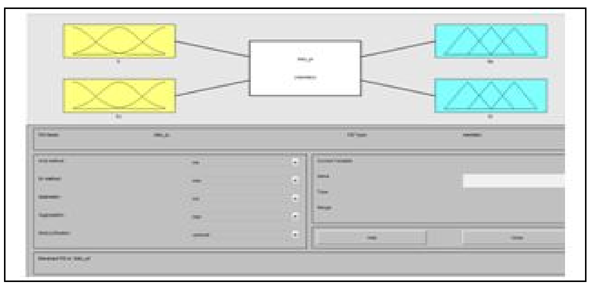
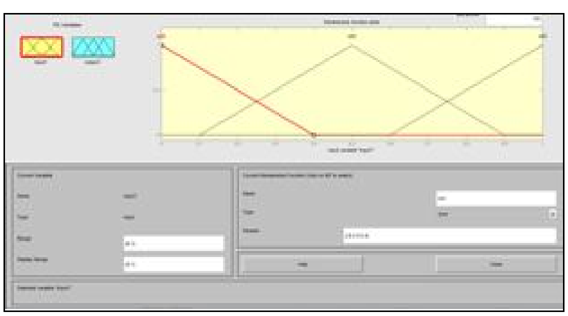


Figure 3: Fuzzy Tool Box

3.2. Fuzzy Language of Input and Output Variables

The fuzzy variable of input variable e is E and ec is EC. The fuzzy variable of output variable k_p and k_i are K_P and K_I. The fuzzy sets of E and EC are all defined as {NB, ZO, PB}, where NB, ZO and PB represent Negative Big, Zero, and Positive Big respectively.

The fuzzy sets of K_P and K_I are defined as {Z, S, M, B}, where Z, S, M and B represent Zero, Small, Medium and Big. The membership functions of E, EC, K_P and K_I are triangular distribution functions. The membership functions for each variable are shown in Figure.4 and Figure 5.



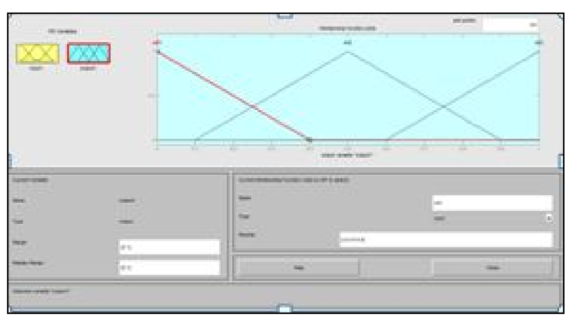


Figure 4: Input Membership Function *Figure 5: Output Membership Function*

3.3. Fuzzy Rules Regulations

The principle of designing fuzzy rules is that the output of the controller can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized as

E/EC	NB	ZO	PB
NB	B	B	M
ZO	M	Z	B
PB	M	B	B

Table 1: Control Rules for K_P

E/EC	NB	ZO	PB
NB	B	B	M
ZO	M	Z	B
PB	M	B	B

Table 2: Control Rules for K_I

Table I and Table II according to the expert in BLDC motor system and simulation analysis of the system. The Mamdani inference method is used as the fuzzy inference mode.

The inference can be written as "IF A AND B THEN C". For example "IF E is NB AND EC is PB THEN K_P is S, K_I is M".K_P and K_I are written the same as 9 fuzzy condition statements.

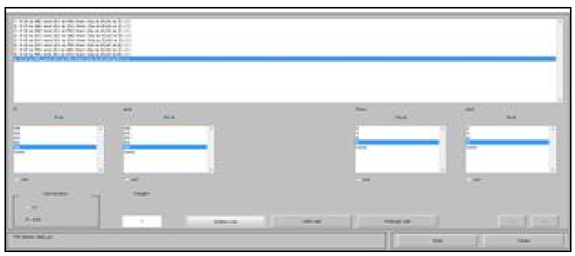


Figure 6: Rule Editor

The output variable can be obtained by the MIN - MAX inference. The weighted average method is adopted for defuzzification. Figure.6 and Figure.7 shows the rule editor and rule Viewer Output while simulation running at 3000rpm rotor speed.

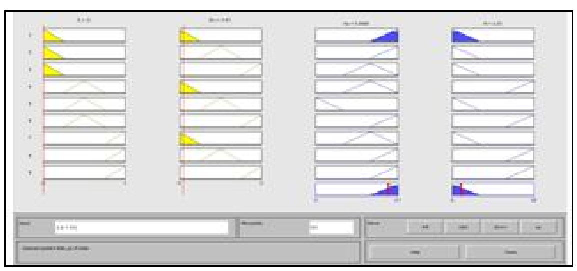


Figure 7: Rule Viewer

4. Simulation Model of BLDC Based on MATLAB

In this MATLAB simulation module, the block diagram and simulation diagram of BLDC motor using Modified fuzzy Tuned PI control is shown in Figure.8 and figure 9. The total system consists of speed loop, current loop, Hysteresis controlled inverter and BLDC motor.

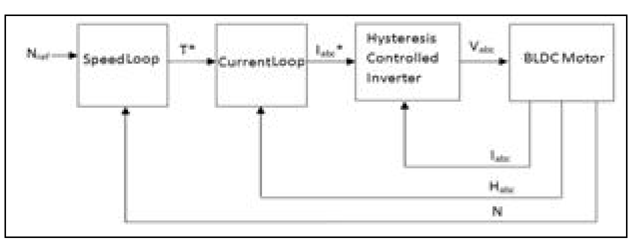


Figure 8: Block diagram of BLDC motor using modified fuzzy Tuned PI control

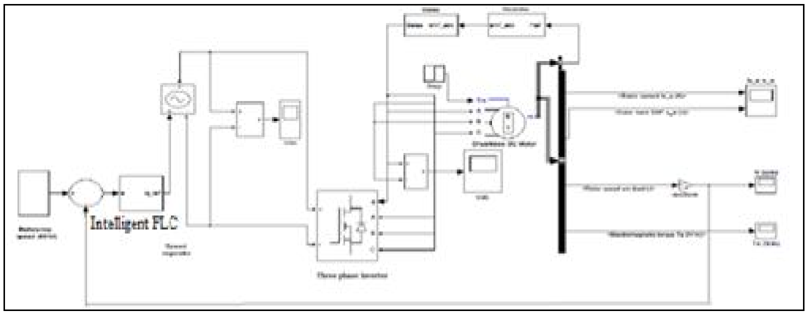


Figure 9: Simulation Diagram of BLDC motor using Intelligent FLC

Speed loop of BLDCM drive is shown in Figure.10. It consists of two inputs such as reference speed and measured speed. Error of reference speed and measured speed is given to the Intelligent FLC. Its output is reference torque of T*.

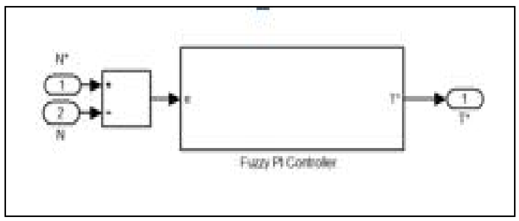


Figure 10: Speed Loop of BLDC motor

The current loop of BLDC motor is shown in Figure.11 It consists of two inputs such as Torque* and Habc. Its output is reference current iabc. Habc is the Hall Effect sensor signals from the motor. It decoded by decoder into Ha,Hb and Hc. Reference torque from the Intelligent FLC is converted into current and multiplied with position signals to produce reference current Iabc*

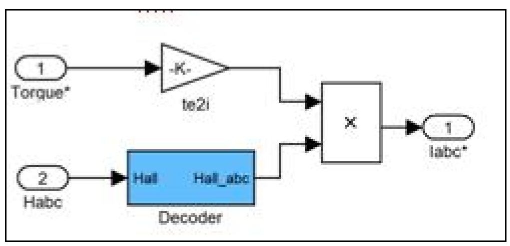


Figure 11: Current loop of BLDC motor

Hysteresis Controlled Inverter consists of a Hex bridge inverter and Hysteresis controller which shows in Figure.11 and Figure 12. Reference current from current loop and actual current from motor are compared to produce a current error. Hysteresis controller receives current error and produces three pulses based on error .These pulses are used to trigger the upper switches in the three arms. The pulse to the upper switch in the arm is inverted and given to the lower switch in the arm. From the inverter three phase voltage is taken out.

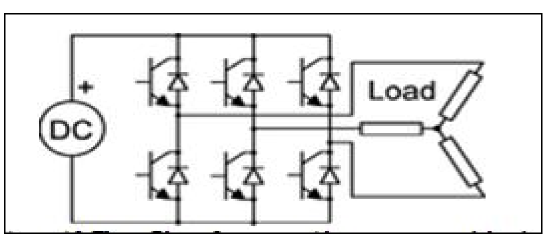


Figure 12: Three Phase Inverter with star connected load

The PWM current controllers [8] are widely used. The switching frequency is usually kept constant. They are based in the principle of triangular carrier wave of desire switching frequency and is compared with the error of controlled signal. The error signal obtained from the sum of reference signal generated in the controller and the negative of the actual motor current feedback from the motor. The voltage signal obtained triggers the gates of the voltage source inverter to generate the desire output. If the error command is greater than the carrier, the inverter leg is held switched to the positive polarity. When the error command is less, the inverter leg is switched to negative polarity. This will generate the PWM signal and the output voltage of the inverter is proportional to the current error command.

5. Simulation Results

The simulation model of BLDC motor using Intelligent FLC has been developed in MATLAB environment with Simulink.
The parameters of BLDC used in this simulation model are,

- Stator Resistance Rs = 1.4 ohm
- Direct axis inductance L_d = 6.6 mH
- Quadrature axis inductance L_q = 5.8 mH
- Moment of Inertia J = 0.00176 Kg.m^2
- Rotor flux linkage φ_f = 0.1546 Wb
- Number of poles P = 6

The E and Ec values corresponding k_P , k_I values are tabulated in table III.

The variations in speed drop, restoration time, and peak overshoot are observed under various conditions and compared with PI and Fuzzy PI controller. The simulation results of BLDC motor at 3000 rpm and comparison of different controller are shown in Figure.13 to Figure.18 and Figure.19. The performance of the BLDC motor based on the proposed scheme has been improved when it is compared with PI and Fuzzy controller.

Limit : E [-2,2] , EC[-2,2] , k_P [0,1] , k_I[0,20]				
Reference Speed	**E**	**EC**	**K_P**	**K_I**
500	2	-1.64	.0667	2.38
1000	-2	-2	0.0892	2.16
1500	-2	1.04	0.0666	3.22
2000	2	1.65	0.0882	17.6
2500	2	0.296	0.0884	17.7
3000	-2	-1.81	0.0888	2.23

Table 3

Reference Speed	Speed Drop for PI Controller	Speed Drop for Fuzzy PI Controller	Speed Drop for Intelligent FLC	Restoration Time for PI Controller	Restoration Time for Fuzzy PI Controller	Restoration Time for Intelligent FLC
500	29.2	25.2	24.4	0.03	0.07	0.04
1000	15.6	13.9	12.1	0.03	0.07	0.04
1500	11	10.3	8.6	0.03	0.1	0.05
2000	8.95	8.45	6.95	0.05	0.1	0.05
2500	7.8	7.2	5.6	0.06	0.12	0.05
3000	6.9	6.5	5	0.08	0.17	0.05

Table 4: Comparison of Different controllers

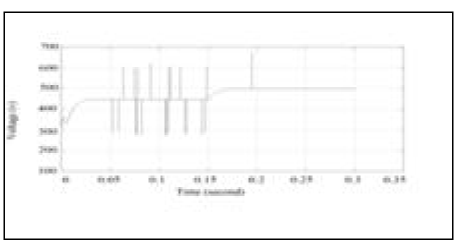


Figure 13: Input Voltage of BLDC motor

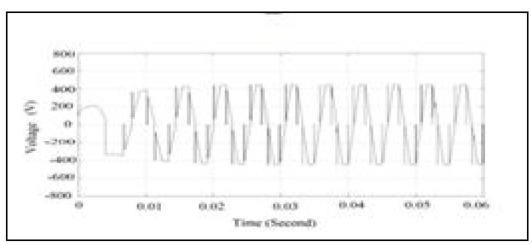


Figure 14: Line Volage Vab of BLDC motor

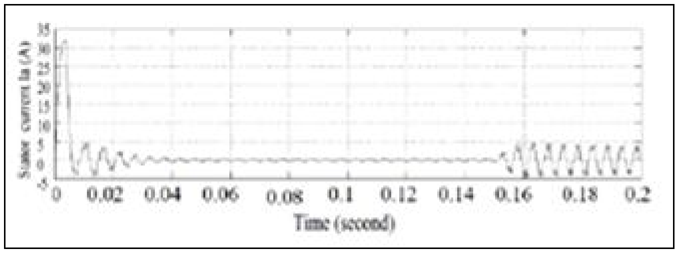


Figure 15: Stator Current IA of BLDC motor

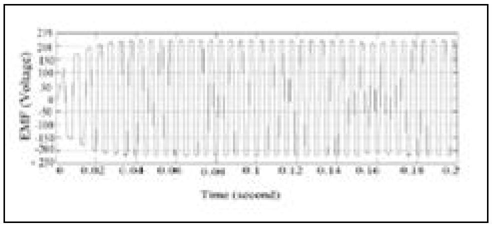


Figure 16: Electromotive Force of BLDC motor

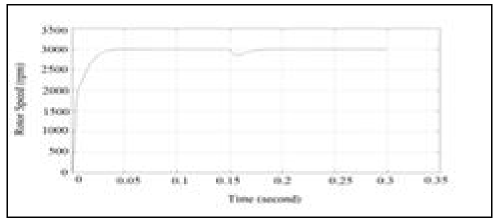


Figure 17: Rotor Speed of BLDC motor at 3000 rpm

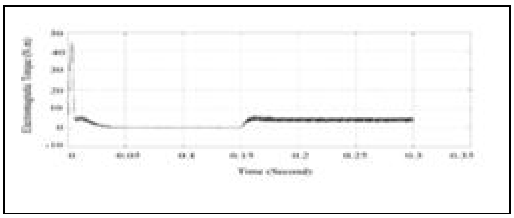


Figure 18: Electromagnetic Torque of BLDC motor

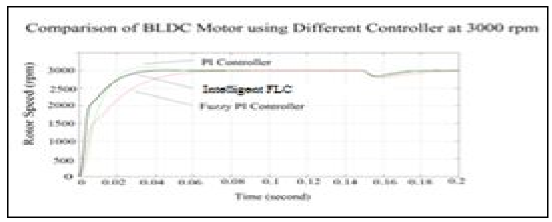


Figure 19: Comparison of BLDC motor at 3000rpm

6. Conclusion

In this paper a novel desirable simulation of closed loop control system for BLDC motor is proposed. The three types of controllers, PI Controller, Fuzzy PI controller and Intelligent FLC are compared and tabulated in table IV. In BLDC motor, Intelligent FLC is used for speed controller and their performances are compared. The performance differences due to the all the three types of controllers are examined for speed. The simulation results proved that PI controller with more speed drop and poor performance under load disturbances with increase in restoration time. The proposed Intelligent FLC gives better speed response with less speed drop with less restoration time. The transient response of speed under load changes using Intelligent FLC is better than PI and fuzzy PI controller with less settling time to reach rated speed. The proposed controller is suitable for industrial applications to maintain constant speed under loaded condition in machining operations.

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