Analysis for Four Quadrant operation and Digital Speed Control of Electronically commutated Motor drive Using Fuzzy logic Controller

B.V. Arun Kumar, G V Marutheswar

ABSTRACT--- This paper presents that the simulation of control of three phase Electronically commutated motor or Brushless Direct Current (BLDC) motor in all four quadrants with Fuzzy Logic controller (FLC). Conventionally the speed control of motors is carried out by conventional motors with using P, PI, PID and some other control techniques. But it provides a chance to occurrence of nonlinearity & uncertainties that causes some internal and external parameter errors. The efficient speed control in all four quadrants can be achieved by using a fuzzy logic controller. The improvisation of electronically commutated motor or Brushless Direct current motor drive through fuzzy logic controller in all four quadrants is done using simulink/MATLAB and Digital speed control of Brushless Direct Current Motor drive with fuzzy logic controller could be done in practical approach using FPGA.

Key words: BLDC motor, proportional Integral (PI) Controller, Fuzzy Logic controller (FLC), Multi or Four quadrant operation, FPGA.

1. INTRODUCTION

In various industrial and home applications Brushless Direct Current motors are used in extent manner. Due to advantages of Brushless DC motors there is improved control schemes to predict the presentation of the motor**.** In a conventional[5] brushed Direct Current motor, the brushes are accountable for making the mechanical contact with a position of electrical contacts on the rotor referred to as the commutator. This forms an electric circuit connecting the DC electrical source and the armature coil windings. While the armature rotates, the motionless brushes come in contact with dissimilar sections of the commutator. The rotating commutator and the brush system shape a set of electrical switches which operate in a series to permit electric current to flow from first to last the armature coils nearby to the field which may be an permanent magnet. In a Brushless Direct Current motor, armature coils do not move, and in its place the permanent magnets rotate. Therefore the armature remains stationary which avoids the difficulty of how to move current to a moving armature. In a Brushless Direct Current motor, the commutator congregation is replaced by an electronic controller which is programmed to perform the coil switching. The major advantages of Brushless DC motor such as elevated efficiency, extended operating life, low down noise, and variable high speed ranges.

Brushless Direct Current motors come across applications in each section of the market such as appliances, industrial control, aviation, etc. Brushless Direct Current motor operation control can be divided into three most important types such as constant load, varying loads and positioning applications. The basic construction of BLDC motor is shown in fig(1).

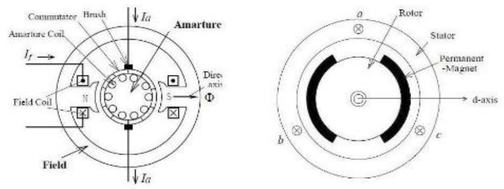

Fig (1): BLDC Motor construction

2. MODELING OF BRUSHLESS DIRECT CURRENT (BLDC) MOTOR DRIVE SYSTEM:

2.1. Modeling of BLDC Motor

abc phase changeable and d-q axis models are used mathematically in BLDC motor. In a BLDC motor the back emf is trapezoidal in nature implies that non sinusoidal mutual inductance among stator and rotor windings, and then renewed in to d-q axis representation. This method is not having a exacting advantage, so we go for adc phase variable technique. Here we assumed that BLDC motor is star linked through isolated neutral. In BLDC motor modeling the subsequent assumptions are not drenched [1].

i. Self and Mutual inductances made i.e.
ii. BLDC Motor is are invariable and stator resistance of all windings is like.
iii. Semiconductor devices are ideal in nature.

The balanced circuit of the BLDC servomotor drive scheme is shown. The line to line voltage equations in matrix form is given as

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$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & -R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} +$$

$$\begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} \quad (1)$$

Mutual inductance (M) is neglected as compared to the self-inductance (L); as a result matrix equation can be rewritten as

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & -R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & -L & 0 \\ 0 & L & -L \\ -L & 0 & L \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix}. \quad (2)$$

Where
L=Self-inductance.
M= per phase Mutual inductance;
R= stator winding Resistance/phase;
e_a, e_b and e_c= phases a, b, and c Back EMFs;
i_a, i_b, i_c= currents of phases a, b, and c, independently.

In BLDC motor, torque generated by means of the BLDC motor can be expressed as

$$T_e=(e_a i_a + e_b i_b + e_c i_c) / \omega = K_t I \quad (3)$$

Where $i_a = i_b = i_c$= I, ω(speed) in r/s, and $K_t$is the torque invariable. Since this torque generated by means of the BLDC motor is used to conquer the differing torques of inertia and load, it can also be written as

$$T_e=T_L + J_M d_\omega /dt + B_M \omega \quad (4)$$

Where T_L = load torque
J_M = Inertia, and B_M= friction invariable of the BLDC servomotor .The load torque can be articulated in requisites of load inertia J_L and friction B_L mechanism as

$$T_L = J_L \frac{d\omega}{dt} + B_L \omega \quad (5)$$

The power output developed by BLDC motor is

$$P = T_e \omega \quad (6)$$

$$E = e_a = e_b = e_c = K_b \omega \quad (7)$$

Where K_b is back Electro Motive Force constant, *E* is back Electro Motive Force per phase and *ω* is the speed in r/s. It possibly will be observed that, the function shown in table I are 120 degree phase shifted.

2.2. Modeling of Back Electro Motive Force (EMF) using Rotor Position:

The phase Back Electro Motive Force(EMF) in the Permanent Magnet BLDC motor is trapezoidal waveform and is the function of the speed ω_m and position of rotor angle $\theta_r$as shown in Fig 3.3.From this, the phase back Electro Motive Force's can be expressed as.

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \quad (8)$$

Where$f_{as}(\theta_r)$, $f_{bs}(\theta_r)$, $f_{cs}(\theta_r)$ are unit function producer to analogous to the trapezoidal induced emfs of the BLDCM as a function of θ_r. The $f_{bs}(\theta_r)$, $f_{cs}(\theta_r)$ are similar to $f_{as}(\theta_r)$ but phase displacement of 120 degrees.

$$f_{as}(\theta_r) = \begin{cases} \theta_r \frac{6}{\pi}, 0 \le \theta_r < \frac{\pi}{6} \\ 1, \frac{\pi}{6} \le \theta_r < \frac{5\pi}{6} \\ (\pi - \theta_r)\frac{6}{\pi}, \frac{5\pi}{6} \le \theta_r < \frac{7\pi}{6} \\ -1, \frac{7\pi}{6} \le \theta_r < \frac{11\pi}{6} \\ (\theta_r - 2\pi)\frac{6}{\pi}, \frac{11\pi}{6} \le \theta_r < 2\pi \end{cases} \quad (9)$$

Accordingly $f_{bs}(\theta_r)$ and $f_{cs}(\theta_r)$ can be designed.

The modeling[7] of the brushless direct current motor includes the reliasation as a function of rotor electrical angle with hall sensors which can be scheduled in below table I.

Table I

Hall sensors modeled as a function of rotor angle

Theta_elec	h_a h_b h_c
$0^0 - 60^0$	1 0 1
$60^0 - 120^0$	0 0 1
$120^0 - 180^0$	0 1 1
180^0-240^0	0 1 0
$240^0 - 300^0$	1 1 0
$300^0 - 360^0$	1 0 0

2.3. Inverter Control

Figure (2) shows a basic block diagram of Brushless Direct Current Motor (BLDCM) control performance for a three phase motor. The circuit uses six power transistors, Metal Oxide Field Effect Transistors or IGBTs. The switches are controlled consequently to provide suitable commutation to the windings in synchronism by means of rotor dislocation, given that the function of the comutator.

In Brushless Direct Current Motor, two phases conduct at a time and the third one drifts and each phase conducts for 120^0 electrical degrees. The commutation moment occurs when the rotor near by a position reflecting 30^0 electrical. From that position, one conducting phase is chopped out and

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the floating phase starts conducting current and so on at an additional position of the rotor subsequent to 120^0 electrical to maximize torque, progress the efficiency and lower the torque ripple

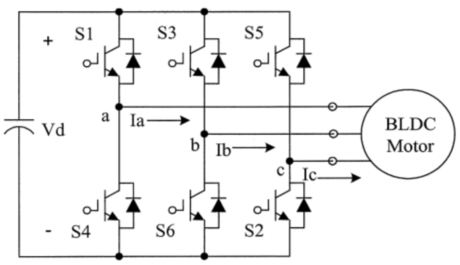

Fig (2): VSI fed BLDC Motor Drive

3. DIGITAL CONTROLLER (FPGA):

Key Components and Features

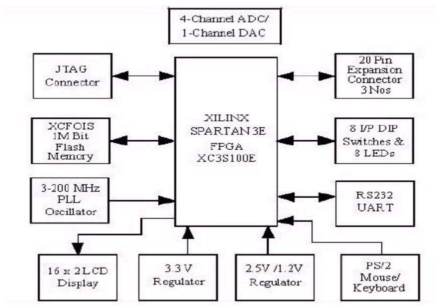

Fig (3) : Spartan-3E Low Cost board block diagram

Figure (3) shows the Spartan-3E Low Cost board block diagram, The four quadrant control of three phase BLDC motor is accomplished with 250,000-gate Xilinx Spartan-3E XC3S250E Field programmable gate array in a 144-Thin Quad Flat Pack package (XC3S250E-TQ144) .The location signals from the three Hall sensors are read from side to side the I/O lines. The PWM module consists of six input and output pin, which is used for generating the PWM pulses for the MOSFET switches. The position or reference speed and the actual speed are fed to the controller.

4. FUZZY LOGIC CONTROLLER (FLC):

The controller with fuzzy logic was applied to the speed controller by replacing the PI controller. The fuzzy logic controlled Brushless Direct Current Motor drive system block diagram is shown in Fig 4.

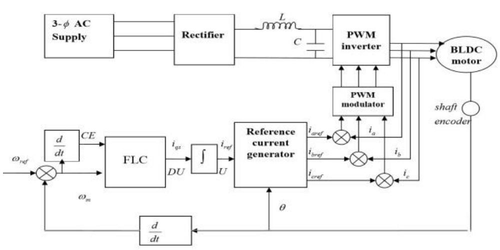

Fig (4) : simulink block diagram representation of Brushless Direct Current Motor with FLC

The controller is calculated the input variable such as speed error(E) and change in error in speed(CE).The output variable is known as position or reference current Iref which is a component of torque and is obtained by using the change in position current at output of controller. The pattern of error signal is observed by controller and corresponding otput DU so that the real speed compared with the reference speed Wref.the FLC is havinf the two input signals,first one is the error and second one is the change in error CE.

The signal is incorporated to produce the real control signal U or current i_{qs}^* . We can write

$$\int DU = \int K_1 Edt + \int K_2 \ CE\ dt \qquad (10)$$

$$U = K_1 \int Edt + K_2 E \qquad (11)$$

where K_1 and K_2 are gain factors together with the summation process.

The membership function for the speed error , change in error and the change in torque or current are shown in Fig. (5),(6),(7). For all changeable seven levels of fuzzy membership function are used. Table .II shows the rule base table that was used in the system.

4.1. Rule base Table:

The following Table I represents the Rules for fuzzy lolgic control

Table II

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

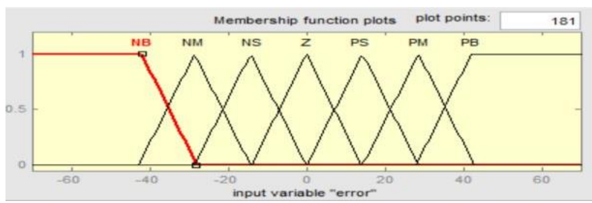

Fig (5): The speed error(E) Fuzzy membership function

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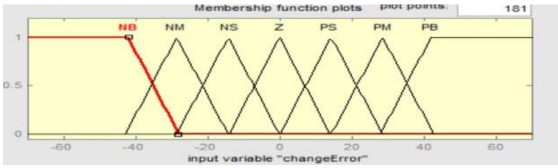

Fig (6): The change in error(CE) Fuzzy membershipfunction

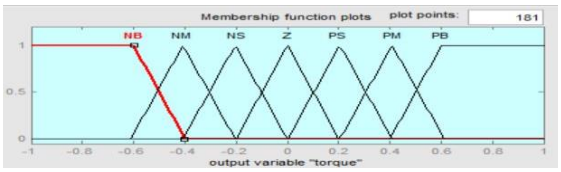

Fig (7) : Change in torque Fuzzy member ship function

5. RESULTS AND DISCUSSION:

Fuzzy Logic Controller

Here we obtain the simulation results of BLDC motor drive with controller.Fig (8) represents speed variation[4] four qudrant operation with zero over shoot.

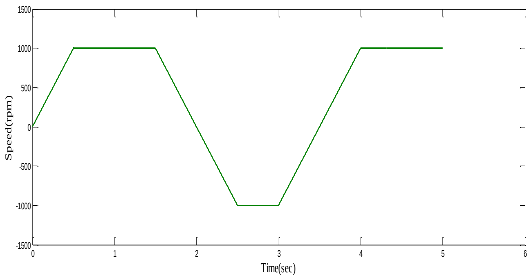

Fig (8): Speed variation from -1000 rpm to +1000 rpm

The variation in the amplitude of the stator back EMFs in one of all the three phases with Fuzzy Logic controller are clearly visible in the scope results shown in Fig(9). The trapezoidal shape is also seen. The trapezoidal what we obtain will be more efficient than compared with PI controller.

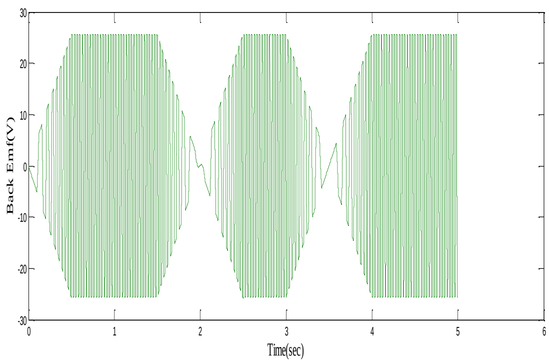

Fig (9): Back emf waveform e_a.

The stator current ia is having more magnitude in motoring mode and reduced to low value in braking mode. Fig (10) represents the stator current in four quadrant mode

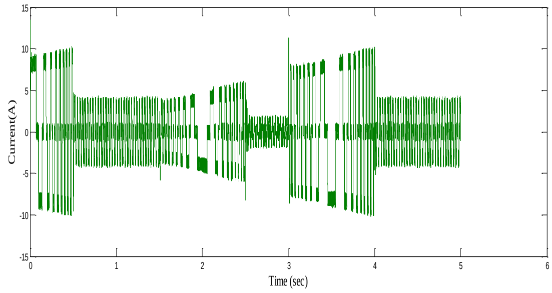

Fig (10): The stator currents of the three phases

Fig(11) represents the battery characteristics of Brushless direct current motor motor with FLC

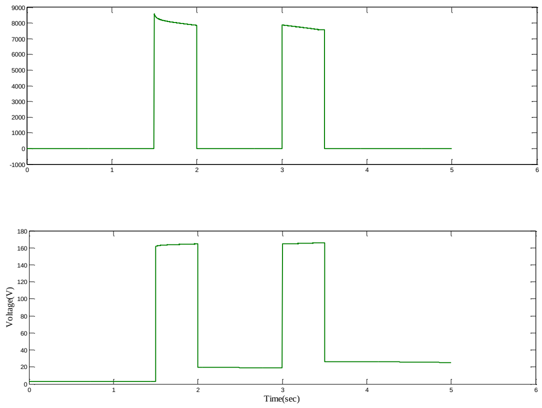

Fig (11): Energy stored in breaking mode with fuzzy logic controller

5.1. Quadrant determination

The following table (II) represents that quadrant determination for given applied torque and speed.

Table II

Time	0	0.5	1.0	1.5	2.0	2.50	2.75	3.0
Reference speed	0	1000	1000	1000	0	-1000	-1000	0
Applied torque	0	0	+1	-1	-1	-1	+1	0
Quadrant	Initial	I	I	II	II	III	IV	-

The speed control performance will shown in table III

Table III

Quadrant	Peak time	Rise time (tr)	Settling time (ts)	Over shoot(%)
Forward motoring(I)	0.5	0.40	0.50	0.0
Reverse motoring(III)	2.5	0.40	2.50	0.0

6. DIGITAL CONTROLLER (FPGA):

Speed control of BLDC motor could be done using Digital controller [3] or FPGA with fuzzy logic controller is shown in Fig(12) below.

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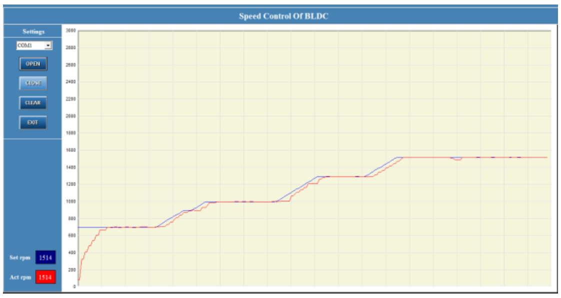

Fig (12): speed control with FPGA using FLC

For different set speeds motor attains nearly same speed (actual speed) using FPGA with fuzzy logic controller which shown in below table IV.

Table IV

s.no	Set speed	Actual speed
1.	1514	1514
2.	1000	999
3.	750	749

7. CONCLUSION:

The speed control of three phase BLDC motor drive in four or multi quadrant operation with Fuzzy logic controllers can be achieved through simulink/matlab and the speed control of motor using FPGA with fuzzy logic controller could be done. The improvisation of BLDC motor drive with FLC in all four quadrants gives the efficient speed control i.e with out over shoot and back emf could be pure trapezoidal and speed control using FPGA could be done.

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