IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 08, Issue 9 (September. 2018), ||V (IV) || PP 30-37

Multi Quadrant Action & Speed Control of Electronically Commutated Motor Drive under Different Load variations

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Abstract-- This paper presents, the Electronically Commutated Motor or Brushless DC motor four quadrant action by the side of with speed control by means of Proportional Integral Differential (PID) controller has presented using MATLAB. Because of its more efficiency, more power density and low maintenance cost Brushless DC motors are used in Industrial and home applications. Subsequent to a lot of research and growth in power electronics and magnetic supplies encompass applications in electric drives in major level. In such applications, PID controller is being implemented with BLDC electrical drive to have control over the speed and current to acquire superior transient and steady-state performance.

Key words: Brushless DC (BLDC) Motor, PID controller, Multi Quadrant Operation.

Date of Submission: 13-09-2018 Date of acceptance: 28-09-2018

I. INTRODUCTION

In various industrial and home applications Brushless DC motors are used in extent manner. Due to advantages of Brushless DC motors there is better control schemes to predict the presentation of the motor. d-q model and abc phase variables models erstwhile used in Brushless DC motor drive systems under different loading conditions [2,7].

So many BLDC simulation models were anticipated [1]-[6] using non-linear state-space equations. Here BLDC Motor used as star linked through neutral grounding but so numerous applications requisite isolating the neutral [8].

Comphrensive simulation studies carry out by using entire control system modeling. This paper deals with motor performance under different loading situation using Proportional Integral Differential (PID) controller. Those situations are starting or no load, variable load, and reverse load conditions. In accumulation to this the multi quadrant operation of BLDC motor is carried out in this paper.

II. MODELING OF THE BRUSHLESS DC (BLDC) MOTOR DRIVE SYSYTEM

The absolute drive system is separated in to seven steps. i.e.

- Modeling of BLDC Motor.
- Closed Loop Controller.
- Modeling of the inverter.
- Modeling of Hysteresis Controller.
- Modeling of Position Current Generator
- Design of PID Controller
- Modeling of Quadrant Determination subsystem

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 made i.e.

I. BLDC Motor is not drenched.
II. Self and Mutual inductances 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 system is shown. The line to line voltage equations in matrix form is given as

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

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

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

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

Where

L=Self-inductance.

M= per phase Mutual inductance ;

R=per phase stator winding Resistance;

e_a, e_b and e_c=Back EMFs of phases a, b, and c, separately;

$i_a, i_b,\ i_c$= phase streams of phases a, b, and c, individually.

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

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

where $i_a = i_b = i_c$= I, ω is the angular velocity in radians per second, and K_t is the torque invariable. Since this electromagnetic torque is used to conquer the differing torques of inertia and load, it can also be written as

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

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

The output power developed by the motor is

$P = T_e \omega$ (6)

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

Where K_b is back EMF constant, E is back EMF per phase and ω is the angular speed in radians per second. The back emf equations modeled as normalized function of rotor location as shown in below Table I.

Table I Back Emf Modeled as a Function of Rotor Angle

Theta_ele	Fa(θr)	Fb(θr)	Fc(θr)
0^o-60^o	$\frac{6\theta r}{} - 1$	+1	-1
60^o-120^o	+1	$3 - \frac{6\theta r}{}$	-1
120^o-180^o	+1	-1	$\frac{6\theta r}{} - 5$
180^o-240^o	$7 - \frac{6\theta r}{}$	-1	+1
240^o-300^o	-1	$\frac{6\theta r}{} - 9$	+1
300^o-360^o	-1	+1	$11 - \frac{6\theta r}{}$

It may be observed that, the function shown in table I are 120 degree phase shifted. The modeling of the motor includes the reliasation of hall sensors as a function of rotor electrical angle which can be scheduled in below table II.

Table II Hall sensors modeled as a function of rotor angle

Theta_elec	h1 h2 h3
0^0 - 60^0	1 0 1
60^o - 120^o	0 0 1
120^o - 180^o	0 1 1
180^o 240^o	0 1 0
240^o - 300^o	1 1 0
300^o - 360^o	1 0 0

2. Closed Loop Controller:

Three phase MOSFET support inverter fed to BLDC motor as shown in fig 1. Firing the semiconductor devices in the inverter using Pulse width modulation gating signals are inject from hysteresis regulator [4]. Here preserve the current invariable within the 60^o interval of one electrical.

It regulates the real current surrounded by the hysteresis group just about the reference currents. The position currents are generated as a result of a position current generator depending in the lead the fixed state operating approach the position currents are of quasi –square wave. They are extended in phase by means of the back-emf in motoring form and beyond phase in braking mode. The quantity of the position current is intended from the position torque. The position torque is obtained by off-putting the amount produced of the PID controller. The PID controller processes the dissimilarity among the position speed and real speed and outputs to the limiter to turn out the reference torque. The real speed is sensed back to the speed controller and processed on to decrease the error in tracking the position speed. As a result, it is called as closed loop control drive method.

3. Modeling of the inverter

The input voltage to BLDC motor abounding from inverter as revealed in fig1. It comprises of two power semiconductor devices on every phase leg. Suitable pairs of switches (S1 to S6) are obsessed based on the input to the hall sensors.

Three phases are commutated for each 60^o .Seeing that sensors are the straight feed back of the rotor position, bringing together among stator and rotor flux is achieved.

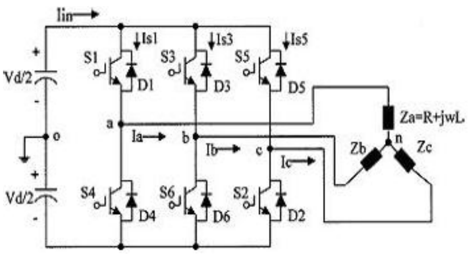

Fig1: Three phase inverter with MOSFET

4. Modeling of Hysteresis Controller

Power device switches are ON/OFF can be done using hysteresis controller which confines the phase currents with hysteresis group. The switching model is given as:

i^{rr} < LL S4 is off and S1 is 0ff.
i^{rr} < LL , S4 is on and S1 is off.
i^{rr} >UL, S3 is on and S6 is off.
i^{rr} < LL, S3 is off and S6 is on.
i^{rr} >UL , S5 is on and S2 is off.
i^{rr}< LL, S5 is off and S2 is on.

UL, LL represents the upper and lower limits of hysteresis group. Thus, by regulating the current preferred quasi-square waveforms can be obtained.

5. Position Current Generator modeling procedure:

The hysteresis controller injected by the intended position currents.. The position current is obtained from the position torque and back-emf invariable. The received or leaving direction of the current is unwavering from hall sensors yield and the operating mode.

6. Design of PID Controller

Proportional Integral-Derivative controllers are generally utilize as a branch of contemporary control systems as they requires pair of parameters to be tuned in it. The PID controllers comprise the facility of eliminating steady-state error owing to integral action and can look forward to output changes owing to derivative action when the system is subjected to a step reference input. The majority ubiquitous PID tuning technique is the Ziegler–Nichols approach, which depends absolutely on parameters got on or after the system step result. The quantity graphic representation of the trial set-up utilized for actualizing PID. The details of The unrelenting control signal $u(t)$of the PID controller is given as a result of

$$u(t) = K_P(e(t) + (1/T_i)\int e(t)dt + T_d de(t)/dt) \quad (8)$$

where, $K_P$is the proportional gain, $T_i$is the integral time invariable, $T_d$is the derivative time invariable, and $e(t)$is the error signal.

The analogous discrete equation for the control signal can be written as

$u(k) = u(k-1) + K_1 \times e(k) + K_2 \times e(k-1) + K_3 \times e(k-2)$ ………… (9)

Where $u(k-1)$ is the preceding control output, $e(k-1)$ is the preceding error, and $e(k-2)$is the error preceding $e(k-1)$.

The constants K_1, K_2 and K_3 are given by

$K_1 = K_P + T\,K_i/2 + K_d/T$…… (10)

$K_2 = -K_P - 2\,K_d/T + T\,K_i/2$……. (11)

$K_3 = K_d/T$……………………….. (12)

$K_i = K_P/T_i$……………………….... (13)

$K_d = K_P T_d$……………………….... (14)

$$T = 1/f$$

Where f is the sample frequency and T is the sample rate. In this work, a simple PID tuning technique that is based on scheme step response is used to determine the controller gains. This technique provides a methodical move toward to regulate the proportional gain in order to diminish the overshoot. The PID controller gains determined are K_P= 11, K_i= 5, and K_d= 0.1 for the BLDC servomotor drive scheme with effective inertia of motor and load J= 0.0025 kg-m^2 , resistance per phase R = 0.7 Ω, and inductance per phase L = 3.2 mH. This system is tested beneath dissimilar operating conditions such as parameters variations, change in reference speed, and load disturbance.

7. Modeling of Quadrant Determination subsystem

The position speed and the real speed find out the operating mode of the motor. Based on the quadrant in which the motor operates, the necessary position currents are generated.

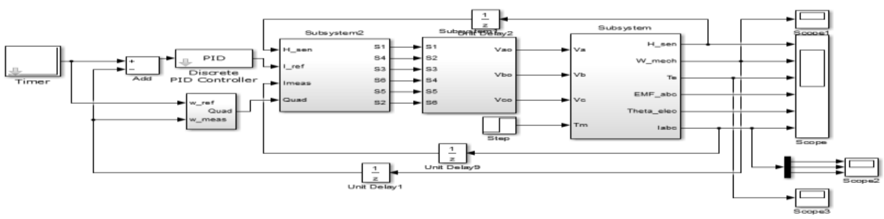

Fig 2: Simulink diagram of BLDC Motor Drive

III. RESULTS AND DISCUSSION

The performance of BLDC motor control system under different loading conditions is examined using motor specifications as listed in Table III.

Table III: MOTOR SPECIFICATIONS

V_{dc}	= 250 volts
V_f	= 0.12
P	= 4

F	= 0.1
R	= 0.7 Ohms
L_t	= 0.000321 Henry
K_e	=0.126 Kt =0.126
J	= 0.0025 kg-m^2

Under subsequent conditions the motor performance erstwhile simulated and analyzed.
1. Starting conditions are discussed.
2. Motor under loaded conditions
3. Motor under variable load conditions.
4. Motor under intermittent conditions
5. Multi quadrant operation of BLDC motor

Output wave forms of speed, torque, rotor angle and current under different conditions shown in below:

1. Starting and no load conditions:

Speeds, Torque, Rotor angle, Current waveforms are shown in Fig 3. The reference speed set to 2000 rpm. The electromagnetic torque of 2.7 N-M is developed to start the motor from standstill. With help of PID controller the actual speed maintained at set value. The variation of current with respect to torque is shown in Fig3.

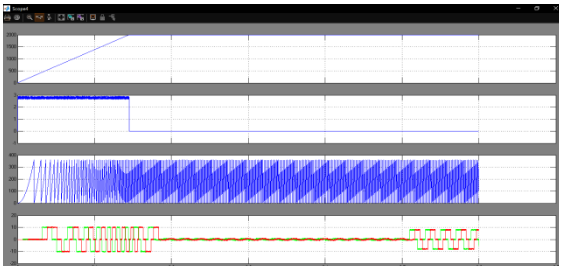

Fig 3 : speed, torque, rotor angle, and current waveforms respectively

2. Motor under Loaded condition:

Settling time and Rise times are calculated for different reference speeds. Here the reference speed is increases in steps the Rise time and Settling time are also increases and it will shown in Table IV.

Table IV

S.No	Reference speed W_{ref}	Settling time t_s(sec)	Rise time t_r(sec)
1	3000	0.22	0.175
2.	4000	0.29	0.225
3.	5000	0.365	0.285

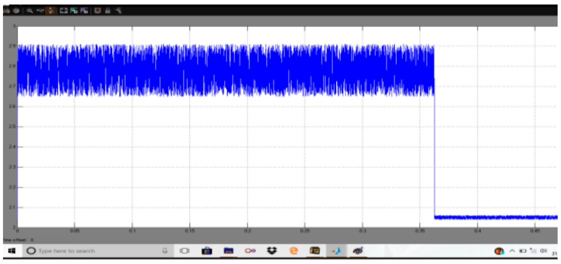

Fig 4: Torque waveform for 5000 rpm

Here the reference speed is set to 5000 rpm then the torque-time characteristics are shown in Fig 4.

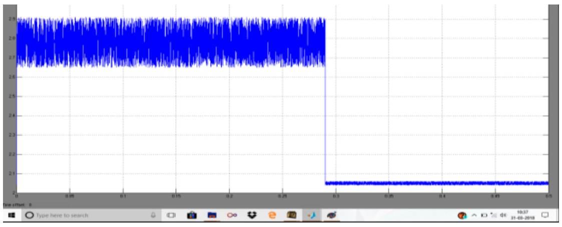

Fig 5: 4000 rpm Torque waveform for

Here the reference speed is set to 4000 rpm then the torque-time characteristics are shown in Fig 5.

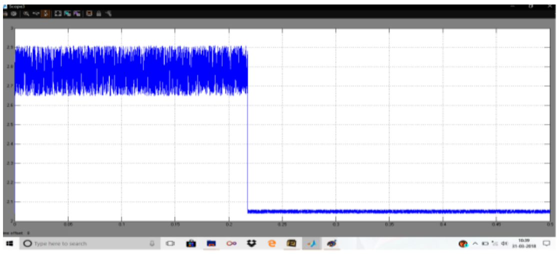

Fig 6: Torque waveform for 3000 rpm

Here the reference speed is set to 3000 rpm then the torque-time characteristics are shown in Fig 6.

3. Motor under Variable load conditions:

Speed-Time characteristics for variable load conditions are shown are shown in Fig7 and Fig8.The time taken to reach the set speed with increment in the load to be met. This can be observed in Table V

Table V

T_L(N-m)	Rise Time
1.0	0.265
2.0	0.665

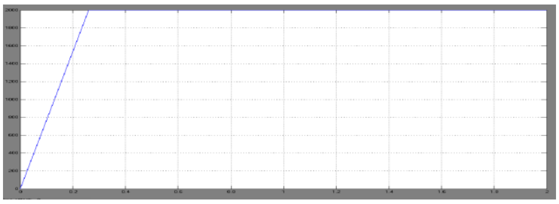

Fig 7: Speed wave form for load torque TL=1.0 N-m

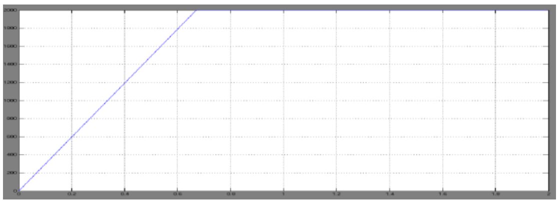

Fig 8: Speed wave form for load torque TL=2.0 N-m

4. Motor under intermittent load conditions

Motor drive system also meets the intermittent loads. Motor under intermittent load conditions are shown in Fig9. Here the speed controller is capable of track the changes in reference speed efficiently.

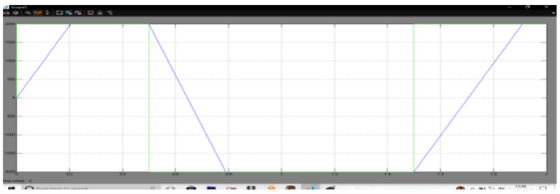

Fig 9: Speed variation in intermittent load conditions

5. Multi quadrant operation of BLDC motor

In motoring mode the magnitude of back- emf until the steady state is reached and in breaking mode the back-emf starts decreasing towards zero. The Fig 10 shows that the change of back-emf from braking mode to motoring mode.

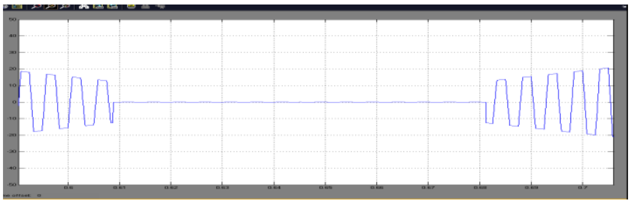

Fig 10 : Back-Emf waveform during change over from barking to motoring operati0n

The torque variation in Multi Quadrant Operation is shown in Fig11.

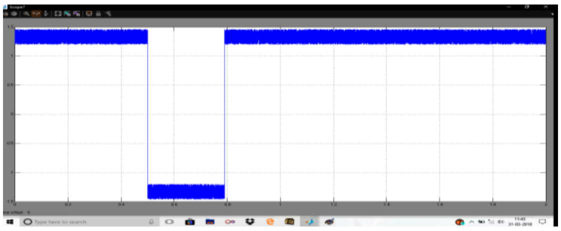

Fig 11: Toque wave form in multi quadrant operation

Fig 12 shows that the speed-torque curve from first quadrant (forward motoring mode) to third quadrant (reverse motoring) via second quadrant (forward braking) in four quadrants.

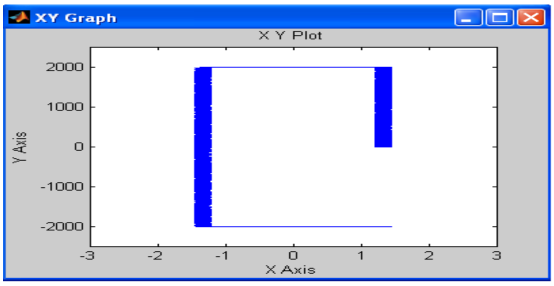

Fig 12 : Speed vs Torque

IV. CONCLUSION

Modeling procedure used in this paper can be useful for simulating the BLDC motor under different loading and operating conditions. Performance of BLDC motor under different loading conditions such as starting and no load , loading, variable load , intermittent load conditions and Multi quadrant operation of VSI fed BLDC motor or Electronically Commutated motor drive can be achieved using Proportional Integral Differential (PID) controller.

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IOSR Journal of Engineering (IOSRJEN) is UGC approved Journal with Sl. No. 3240, Journal no. 48995.

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