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Performance Analysis of Space vector pulse width modulation based Sensor less Field oriented control of Brushless DC motor

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Abstract: This paper presents an approach to Field oriented control (FOC) of Brushless DC (BLDC) motor producing significantly less torque ripple. The sensorless Field oriented control of BLDC motor is more efficient in terms of torque generation compared to back emf zero crossing technique. It allows independent control of torque and rotor flux by controlling the torque and flux producing current components. The space vector pulse width modulation generates switching pulses for inverter switches aids improved system performance with reduced total harmonic distortion compared to other PWM technique. The simulation of SVPWM based sensorless indirect field oriented control of BLDC motor with necessary vector (Clark-Park) transformation is carried out using MATLAB/SIMULINK.

Keywords: Brushless DC motor, field oriented control, space vector pulse width modulation, Clark-park transformation.

I. INTRODUCTION

A Brushless DC motor is a permanent magnet synchronous motor which uses rotor position sensors for efficient commutation of inverter switches. It overcomes the drawback of brushed DC motor as it does not have mechanical commutator and brushes. Presently PMBLDC motors are replacing DC motors, universal motors and induction motors in low power applications since they are efficient, requires less maintenance and smaller in size. For inverter switching either sensor or sensorless techniques can be used. In some applications where the motor is enclosed like compressor sensored method is impractical hence sensorless is preferred. Presently the Parmanent magnet BLDC motor is becoming widely used in consumer, industrial and electric vehicle applications as they have advantages such as high efficiency, fast dynamic response and better speed versus torque characteristics. Also they are finding applications in variable speed control of AC motor drives.

The Indirect field oriented control technique is one of the efficient and effective motor control schemes which allow smooth torque operation. It is extensively used in high performance AC and DC motor drives [1]. It can be accomplished by decoupled control of electromagnetic torque and rotor flux using co-ordinate transformation which improves transient response of motor. The vector or FOC algorithm provides different scheme of rotor position estimation efficiently controls the motor without the use of any mechanical rotating sensor and provides better torque performance and reduced torque ripple.

II. SYSTEM STUDY

The block diagram of system study is shown in Fig.1. The BLDC motor load is connected to the constant DC voltage source through 3-phase voltage source inverter (VSI). Using the position encoder rotor angle and speed can be sensed and are used as feedback signals. The field oriented control scheme provides reference voltage signal to the Space vector Pulse width modulation which generates switching sequence for the inverter.

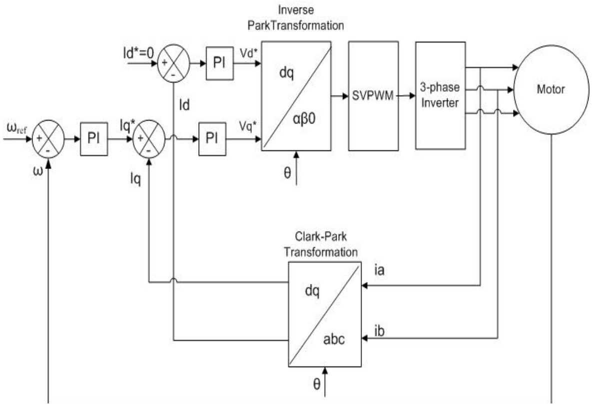

Fig. 1. Block diagram of the SVPWM based field oriented control of PMBLDC motor

III.BLDC MOTOR MODELLING

The PMBLDC motor modelled here is a 3 phase 8 pole motor. Its modelling is similar to that of synchronous machine. The three phase star connected BLDC motor equations are as follows:

$$V_a = R_a i_a + (L-M)\frac{di_a}{dt} + e_a \tag{1}$$

$$V_b = R_b i_b + (L-M)\frac{di_b}{dt} + e_b \tag{2}$$

$$V_c = R_c i_c + (L-M)\frac{di_c}{dt} + e_c \tag{3}$$

Assuming all the phase resistances is equal in balanced three phase system,
$R_a = R_b = R_c = R$
The phase voltage equation in matrix form is as below:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} \mathrm{L-M} & 0 & 0 \\ 0 & \mathrm{L-M} & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \tag{4}$$

Where, Va, Vb, Vc = terminal phase voltage [V], R = armature resistance [Ω], L = armature self inductance [H], M = mutual inductance between any two phases, i_a, i_b, i_c = stator phase current [A], e_a, e_b, e_c = motor back emf [V]
Back emf of each phase is displaced by 120° phase shift. The back emf equation for each phase is as follows:

$$e_a = K_w f(\theta_e)\omega \tag{5}$$

$$e_b = K_w f(\theta_e - \frac{2\Pi}{3})\omega \tag{6}$$

$$e_c = K_w f(\theta_e + \frac{2\Pi}{3})\omega \tag{7}$$

The function f( ) provides the trapezoidal waveform of back emf signal. For one cycle of this function, its equation can be written as:

$$f(\theta) = \begin{cases} 1, (0 \le \theta_e < \frac{2\Pi}{3}) \\ 1 - \frac{6}{\Pi}(\theta_e - \frac{2\Pi}{3}), (\frac{2\Pi}{3} \le \theta_e < \Pi) \\ -1, (\Pi \le \theta_e < \frac{5\Pi}{3}) \\ -1 + \frac{6}{\Pi}(\theta_e - \frac{5\Pi}{3}), (\frac{5\Pi}{3} \le \theta_e < 2\Pi) \end{cases} \tag{8}$$

where, Kw = back emf constant [V/ rad.S-1], θ_e = rotor position in electrical degree, ω = rotor speed [rad.S-1]

Rotor mechanical and electrical angle are related as follows:

$$\theta_e = \frac{P}{2}\theta_m \tag{9}$$

The electromagnetic torque equation can be expressed as:

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{10}$$

In BLDC motor the electromagnetic torque depends on the current, motor speed and back emf. Hence the instantaneous torque equation is given as:

$$T_{em} = \frac{1}{\omega}(e_a i_a + e_b i_b + e_c i_c) \tag{11}$$

Where, P = number of poles, T_L = load torque [NM], J = moment of inertia [Kgm2], B= friction constant [Nms.rad.s-1]

IV. INDIRECT FIELD ORIENTED CONTROL SCHEME

Step1: The control process starts by measuring the armature currents. Instead of three, two of three phase currents i_a, i_b are sensed. The third phase current i_c is calculated by using the relation as given below:

$$i_a + i_b + i_c = 0 \tag{12}$$

The combined vector representation of current in three reference frames is shown in Fig. 2.

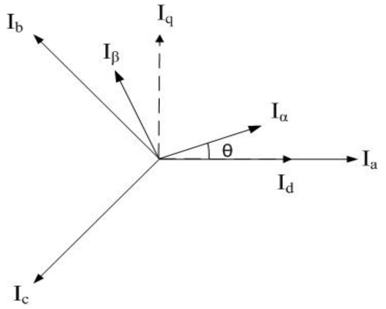

Fig. 2. Combined current vector representation

Step 2: The 3-phase stator currents are converted into the (α-β) two dimensional orthogonal system using Clark's transformation as presented below:

$$i_\alpha = i_a \tag{13}$$

$$i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \tag{14}$$

Step3: The time variant two dimensional (α,β) currents generated in step 2 are transformed to the d,q rotational reference frame. This conversion is called as Park's transformation.

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta \tag{15}$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \tag{16}$$

Where, θ is the rotor flux position.

The currents i_d, i_q are flux and torque controlling components respectively and are time invariant in nature.

Step 4: For permanent magnet machine, i_d reference value is generally kept zero, whereas the reference value for i_q is generated from torque command which is generated from the speed control loop. These two references are compared with actual feedback signals. The error signals generated from comparator are then processed using PI controllers. The outputs of PI controllers give the reference (V_d, V_q) voltge vectors.

Step 5: Using Inverse Park's transformation the voltages in d,q rotating reference frame are translated back to the (α,β) stationary orthogonal reference frame.

$$V_\alpha = V_d \cos\theta - V_q \sin\theta \qquad (17)$$

$$V_\beta = V_d \sin\theta + V_q \cos\theta \qquad (18)$$

The resulting voltage vectors V_α and V_β are then used to perform Space vector pulse width modulation.

V. SPACE VECTOR PULSE WIDTH MODULATION

Space vector modulation is an advanced computational intensive technique used for modulating the inverter output voltage and is the best PWM technique for variable speed drive applications. It is used to generate sine wave that gives higher voltage to the motor with lower total harmonic distortion. The SVPWM technique utilizes DC bus voltage more efficiently and generates less harmonic distortion compared to other PWM methods.

Here the three phase system is represented in a vector rotating with angular velocity with respect to stationary orthogonal reference α-β axes where α-axis coincides with V_a phase voltage axis. In this modulation technique revolving reference voltage vector is taken as voltage reference. The magnitude and frequency of fundamental components in the line side are controlled by the magnitude and frequency of reference voltage vector. The vector representation of SVM is as shown in Fig. 3.

There are eight possible switching states (V_0 to V_7) for 3 phase 2-level inverter powering from DC voltage source Vdc. The ON devices of inverter, switching states and corresponding phase and line voltages machine are summarized in Table 1.

TABLE I SUMMARY OF SWITCHING STATES, PHASE VOLTAGE AND LINE TO LINE VOLTAGE

State	**Space voltage vector**	**ON devices**	**Phase voltage**			**Line voltage**		
			V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_0
0	V0=(000)	S4 S6 S2	0	0	0	0	0	0
1	V1=(100)	S1 S6 S2	2/3	-1/3	-1/3	1	0	-1
2	V2=(110)	S1 S3 S2	1/3	1/3	-2/3	0	1	-1
3	V3=(010)	S4 S3 S2	-1/3	2/3	-1/3	-1	1	0
4	V4=(011)	S4 S3 S5	-2/3	1/3	1/3	-1	0	1
5	V5=(001)	S4 S6 S5	-1/3	-1/3	2/3	0	-1	1
6	V6=(101)	S1 S6 S5	1/3	-2/3	1/3	1	-1	0
7	V7=(111)	S1 S3 S5	0	0	0	0	0	0

The desired 3 phase output voltage equations are described as:

$$V_a = V_m \cos\omega t \qquad (19)$$

$$V_b = V_m \cos(\omega t - 120^o) \qquad (20)$$

$$V_c = V_m \cos(\omega t + 120^o) \qquad (21)$$

The reference voltage can be expressed as:

$$V_{ref} = \sqrt{\frac{3}{2}} V_m e^{j\theta} \qquad (22)$$

Where, $\theta = \omega t = 2\pi f t$

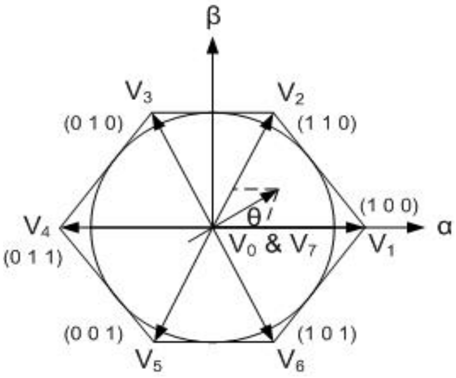

Fig. 3. SVPWM vector representation

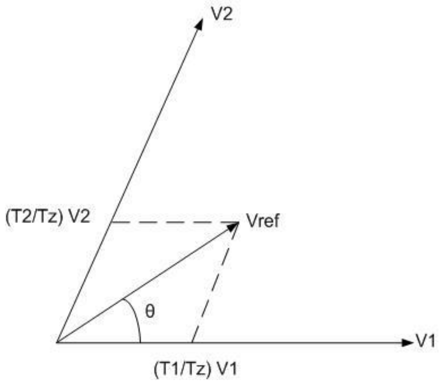

Fig. 4. Sector 1 representation

The reference voltage is the summation of adjacent vectors. The vector representation of sector 1 with reference voltage is as shown in Fig. 4.

$$\overrightarrow{V_{ref}} T_Z = \overrightarrow{V_1} T_1 + \overrightarrow{V_2} T_2 \qquad (23)$$

$$\because \phi = \theta - (N-1)60 \qquad (24)$$

Where Tz= 1/fs, fs is switching frequency, Φ is angle between each vector within 0 to 60 degree , N = number of sector from 1 to 6

Switching periods T1, T2, T0 can be determined using the equations given below:

$$T_1 = T_z \frac{2}{\sqrt{3}} \frac{V_{ref}}{V_1} \sin(60-\phi) \qquad (25)$$

$$T_2 = T_z \frac{2}{\sqrt{3}} \frac{V_{ref}}{V_2} \sin(\phi) \qquad (26)$$

$$T_0 = T_z - (T_1 + T_2) \qquad (27)$$

Table 2. gives the summary of switching time at each sector.

TABLE II CALCULATION OF SWITCHING TIME AT EACH INTERVAL

Sector	**Upper switches (S1,S3,S5)**	**Lower switches (S4,S6,S2)**
1	$S_1=T_1+T_2+T_0/2$ $S_3=T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_0/2$ $S_2=T_1+T_2+T_0/2$
2	$S_1=T_1+T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_2+T_0/2$
3	$S_1=T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5=T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_0/2$
4	$S_1=T_0/2$ $S_3=T_1+T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_2+T_0/2$ $S_2=T_0/2$
5	$S_1=T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_0/2$
6	$S_1=T_1+T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_1+T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_2+T_0/2$

VI. SIMULATION AND RESULTS

The simulation is done using MATLAB/SIMULINK. The SVPWM based field oriented control of BLDC motor Simulation is as shown in Fig. 5.

A. *MATLAB/SIMULINK simulation*

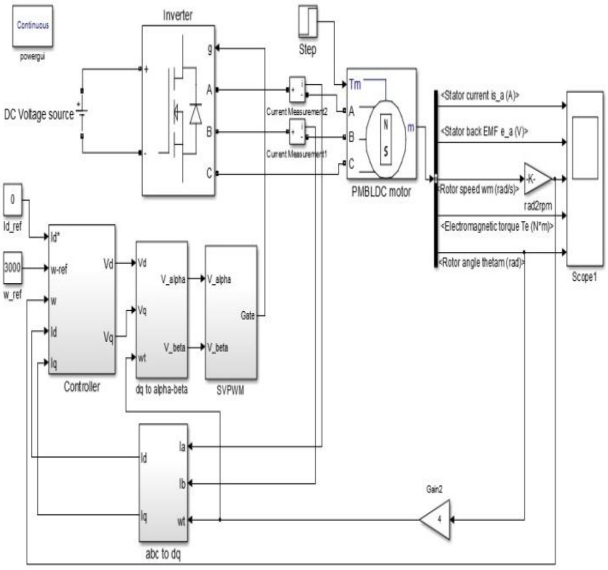

Fig. 5. Simulation block diagram of SVPWM based Field oriented control of BLDC motor

The simulation of three phase inverter fed PMBLDC motor drive with space vector PWM (SVPWM) is as shown in above figure. Here, the 24V constant DC source supplies the motor load through voltage source inverter (VSI).

The system proposed consists of outer speed control loop and inner current control loop. The reference speed command is set as 3000rpm. The specifications of motor parameters are summarized in Table 3.

TABLE III MOTOR PARAMETERS

Parameter	**Value**
Input DC voltage	24 V
Fundamental frequency	50 Hz
Switching frequency	10 KHz
Stator Resistance	0.36 Ω
Stator inductance	0.6m H
Torque constant	0.036 Nm/A
Moment of inertia	4.6u Kg.m^2
Pole pairs	4

B. *Results and Discussion*

The inverter line to line voltage (Vab) output responce is shown in Fig. 6. and Fig. 7. Shows trapezoidal back emf response of BLDC motor.

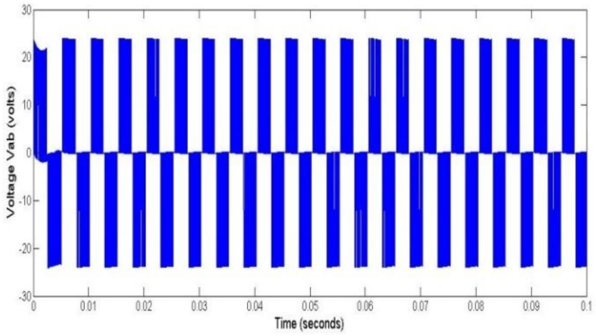

Fig. 6. Inverter line voltage

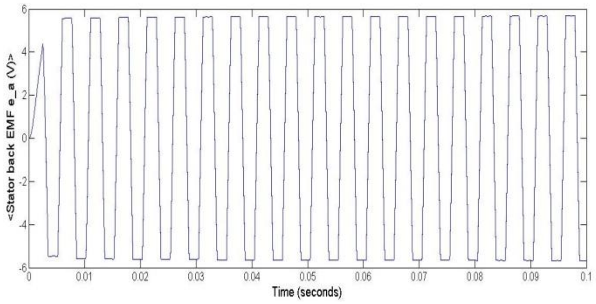

Fig. 7. Trapezoidal back emf response of motor

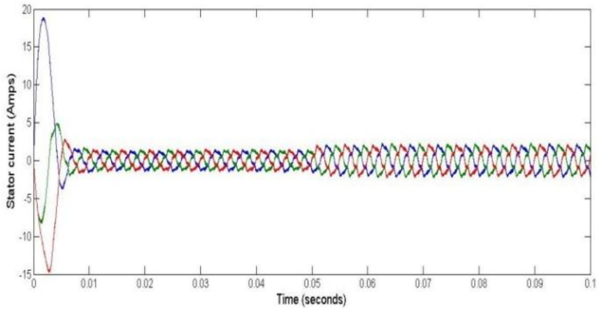

Fig. 8. Three phase stator current

Fig. 8. Shows the three phase motor current. Initially the motor current is high and when it reaches steady state the current will be of 2.3A.

The speed response of BLDC motor is as shown in Fig. 9. From this figure it is observed that the motor speed reaches steady state within 0.06 sec.

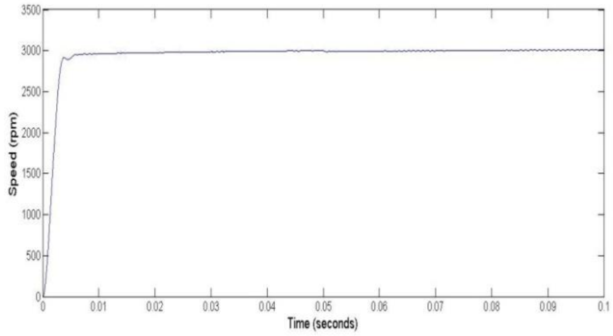

Fig. 9. Motor speed

Fig . 10. shows the electromagnetic torque response of motor. For step change in load torque at 0.05 sec the variation in torque output is shown Fig. 11. From this figure it is observed that the time duration of transient response is very small.

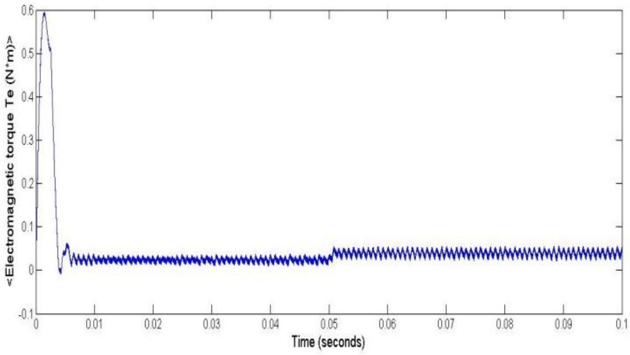

Fig. 10. Electromagnetic torque

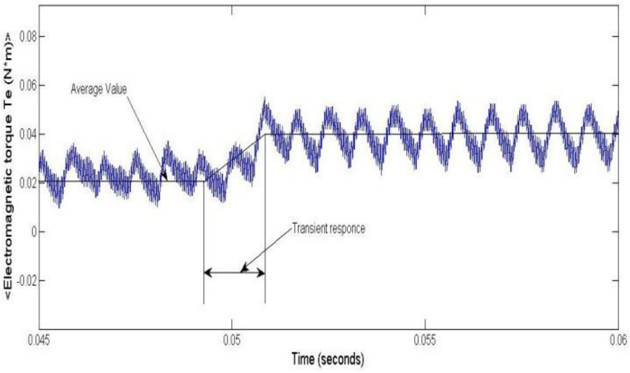

Fig. 11. Electromagnetic torque for change in load torque

VII. CONCLUSION

In this paper, an indirect field oriented control of Brushless DC motor using Space vector PWM technique has been verified using MATLAB/SIMULINK. From the simulation results, it is observed that the field oriented control technique gives better performance in improving dynamic response of motor and high starting torque with reduced torque ripple while maintaining the other parameters of the system.

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