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Investigation of Slim Type BLDC Motor Drive with Torque Ripple Minimization using Abridged Space-Vector PWM Control Method

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ABSTRACT

Brushless DC (BLDC) motors are becoming an increasingly popular motor of choice for its unique characteristics. The BLDC motor drive is assumed to have trapezoidal back-electromotive force (EMF), rectangular phase currents and together produces the desired torque. However, practical back-EMF waveform might not be exactly trapezoidal because of current ripple, design considerations and manufacturing limitations. The adverse effect is the torque ripple generated due to the current ripple that causes mechanical vibration, acoustic noise and affects the accuracy of speed and position control which is not desirable in motor operation. In this paper an algorithm is developed to control and minimize the generated torque ripple using Space Vector Pulse Width Modulation (SVPWM) scheme. The efficiency improvement of slim type BLDC motor is confirmed using MATLAB environment and low cost TI Piccolo F28035 microcontroller (MC).

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1. INTRODUCTION

The BLDC motors are one of the motor types rapidly gaining popularity. As the name implies, BLDC motors do not use brushes for commutation, instead they are electronically commutated. They have many advantages over brushed DC motors in terms of better speed versus torque characteristics, high dynamic response, long operating life and high speed ranges [1]. In addition, the ratio of torque delivered to the size of the motor is higher, making it suitable in applications where space and weight are critical factors [2]. A demand for the motor, especially slim-type BLDC motor, is expected to increase since the minimizing trend of the actuators is getting attention. The phase inductance of the slim-type BLDC motor is large and it causes a lagging of current compared with back EMF in wide range of speed [3]. This causes reduced motor efficiency and increased phase current.

As a result, significant torque pulsations may arise due to the back EMF deviation from the ideal rectangular waveform, phase current ripple due to commutation events, PWM and cogging. Thus, torque ripple is generated due to the non-linear increase in the phase current ripple [4]. It is desirable to minimize torque ripple, since it may cause unacceptable speed ripple, mechanical vibration and acoustic noise. Hence various researchers have investigated this commutation torque ripple and proposed several methods. An alternative explanation for the cause of commutation torque ripple was presented in [5].

Furthermore, the behaviour of PMBLDC drive to the vector analysis in the stationary plane in which the current vector follows the petal-shape trajectory is extensively examined [6]. A design is implemented for current control rule in which the duty cycle of PWM is regulated in real time by measuring the wave function of back EMF and provides torque automation control [7]. The development of a new low cost IC for control of BLDC motors and a simple novel digital PWM control has been implemented for a trapezoidal BLDC motor drive system [8]. Another researcher proposed an approach which separates the ZCP detections from speed adjustment, and makes the shoot-through vector not influence the motor speed -adjustment directly but through zero and active vectors [9]. The traditional all-turn-off current limit logic is replaced by half turn- off logic. An improved current sampling scheme is presented which induces failure of current limiting after the elimination of reversal current [10]. By comparative study with PMSM, BLDC motor has advantages of high speed adjusting performance and power density [11]. So, the BLDC motor is the ideal choice for the CMG's gimbal system. Therefore, its application in the high precision servo system is restricted due to the generated electromagnetic torque ripple [12]. For the commutation torque ripple, Calson have stated that related torque is related to current and varies with speed [13]. Later Chuang, have analyzed the influence of different pulse width modulation (PWM) patterns on the commutation torque ripple according to the BLDC motors with ideal trapezoidal back EMF [14]. The control scheme for the efficiency improvement of slim type BLDC motor is realized in [15]. Direct torque control for reducing commutation torque ripple in permanent magnet BLDC motor and its complexity is studied from [16].

This paper proposes a SVPWM based approach for controlling the switching pulses to the VSI and thereby controlling the speed of the motor with the minimized torque ripple. Further, the modeling of space vector sector equation in section IV leads to minimization of torque ripple respectively. The efficiency improvement of slim type BLDC motor is confirmed using MATLAB environment and low cost TI Piccolo F28035 microcontroller (MC).

2. MATHEMATICAL MODELING of BLDC MOTOR

The characteristic analysis depending on the drive type [17] and torque ripple due to commutation in BLDC motor [18] have been studied. The voltage equation of the BLDC motor is given as,

$$V_a = i_a R_a + L_a \frac{di_a}{dt} + M_{ab} \frac{di_b}{dt} + M_{ac} \frac{d_{ic}}{dt} + e_a \tag{1}$$

$$V_b = i_b R_b + L_b \frac{di_b}{dt} + M_{ba} \frac{di_a}{dt} + M_{bc} \frac{d_{ic}}{dt} + e_b \tag{2}$$

$$V_c = i_c R_c + L_c \frac{di_c}{dt} + M_{ca} \frac{di_a}{dt} + M_{cb} \frac{di_b}{dt} + e_c \tag{3}$$

Here e_a, e_b, e_c are the back emf of BLDC motor. The mathematical model of BLDC motor can be expressed in matrix form as,

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

Where L_a, L_b and L_c are self-inductance and M_{ab}, M_{ba}, M_{bc}, M_{cb}, M_{ac} and M_{ca} are mutual inductance. For simplification all self-inductance are assumed as L and all mutual inductance are assumed as M. Since it is a balanced three phase system all resistance are equal and therefore,

$$R_a = R_b = R_c = R \tag{5}$$

Replacing the value of self-inductance, mutual inductance and three phase resistance, Equation 4 can be written as,

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (6)$$

The electromagnetic torque of the BLDC motor is expressed as,

$$T_e = J\frac{d\omega}{dt} + B\omega + T_l \quad (7)$$

In terms of angular velocity, the electromagnetic torque of BLDC motor is expressed as,

$$T_e = \frac{1}{\omega}\left(e_a i_a + e_b i_b + e_c i_c\right) \quad (8)$$

The transfer function of BLDC motor is,

$$G(s) = \frac{1/k_e}{T_m T_e s^2 + T_m s + 1} \quad (9)$$

Where T_m and T_e are the mechanical time constant and electrical time constant respectively.

3. SPACE VECTOR PULSE WIDTH MODULATION

The SVPWM technique has become a popular PWM technique for three-phase voltage-source inverters (VSI) in applications such as control of AC induction and permanent-magnet synchronous motors. The drawbacks of the sinusoidal PWM and hysteresis-band current control are reduced using this technique. Instead of using a separate modulator for each of the three phases in the conventional techniques, the complex reference voltage vectors processed as a whole. Therefore, the interaction between the three motor phases is considered.It has been shown, that SVPWM generates less harmonic distortion in both output voltage and current applied to the phases of an AC motor and provides a more efficient use of the supply voltage in comparison with sinusoidal modulation techniques [19]. SVPWM provides a constant switching frequency and therefore the switching frequency can be adjusted easily.
Although SVPWM is more complicated than sinusoidal PWM and hysterisis band current control, it may be implemented easily with modern DSP based control systems [20]. This technique is commonly used for the control of AC induction, BLDC and Switched Reluctance motors.

A three-phase inverter via a series of switches is connected to a three-phase BLDC motor through three output legs. The switches must be controlled so that at no time, both switches in the same leg is turned on or else the DC supply would be shorted. This requirement may be met by the complementary operation of the switches within a leg. i.e., if A+ is on then A− is off and vice versa. This leads to eight possible switching vectors for the inverter, V0 through V7 with six active switching vectors and two zero vectors.The selection of vectors depends upon the reference vector, terminal voltage and time duration. Figure 1 shows the basic layout of space vector representation.

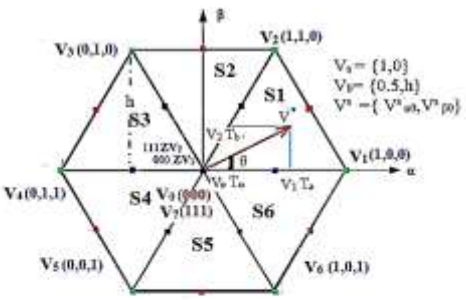

Figure 1. Space vector representation

The reference vector is represented in a αβ-plane. This is a two-dimensional plane transformed from a three-dimensional plane containing the vectors of the three phases. The switches being ON or OFF is determined by the location of the reference vector on this αβ-plane.There exists six switches namely 1, 2, 3, 4, 5, and 6 among which the switches 1, 3, 5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (Va, Vb, Vc) is positive (+VDC). If the upper switches are zero, then the terminal voltage is zero).The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100, 110, 110 and 111. This means that there are 8 possible switching states, for which two of them are zero switching states and six of them are active switching states. These are represented by active (V1-V6) and zero (V0) vectors. The zero vectors are placed in the axis origin.V_{ref} can be found with two active and one zero vector. For sector 1, Vref can be located with V0, V1 and V2. Similarly, for each sector there are 7 switching states for each cycle. It always starts and ends with a zero vector. This also means that there is no extra switching state needed when changing the sector. The uneven numbers travel counter clockwise in each sector and the even sectors travel clockwise. The duty cycle for sector 1, goes through the switching states: (000-100-110-111-110-100-000), one round and then back again. Following the pattern for each sector, results in an ON/OFF waveform for each sector and phase. Each switch has its switching information depending on where the reference vector is located. For the switches to know that it should be switched ON at these specific times, requires a timer that can give this information. Devices like a ramp or a repeated sequence can be used as a reference. Thus the base of the SVPWM lies on the reference vector, time interval and the switching sequence.Note that, the vectors V0 and V7 are the zero vectors and V1 to V6 are the active vectors respectively.

4. PROPOSED SVPWM TOPOLOGY for TORQUE RIPPLE MINIMIZATION

The SVPWM scheme for slim type BLDC motor is different from that of permanent magnet synchronous motor for its turn-off phase and trapezoidal back electromotive force. This scheme is implemented for its superiority over other PWM techniques. SVPWM has increased output without much distortion. The output is about 90.7% which is 15% greater than sinusoidal PWM 78.55%. This method compares a single modulating wave with a carrier instead of using three waves.

When the neutral of the load is connected to a DC supply voltage, it considers interaction among phases whereas other PWM scheme does not. Switching losses computation is easier in SVPWM compared to sine PWM which depends on MI. Figure 2 shows proposed closed loop control system for torque ripple minimisation using SVPWM scheme.

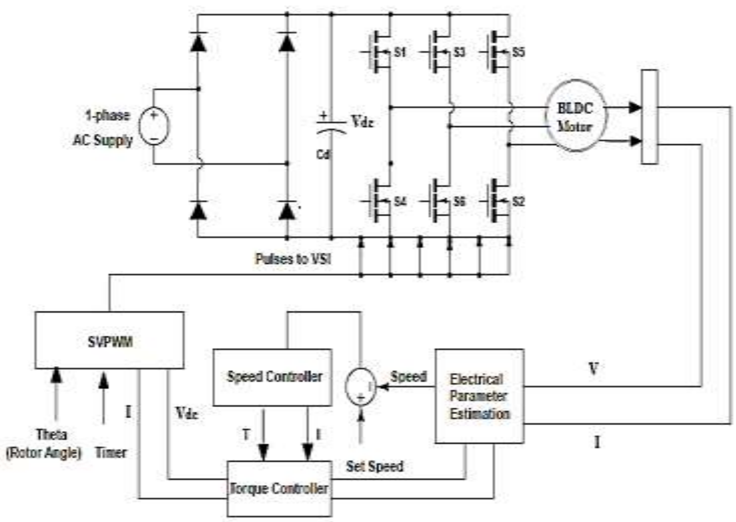

Figure 2. Schematic Layout of The Proposed Topology

The schematic layout is realized in MATLAB environment. MOSFET's are used for its unique superiorities over other switching devices. The electrical parameter estimation is done by modeling of the mentioned equations. The sector N is given by,

$$N = [0.5U_\alpha] + \left[\left(\frac{\sqrt{3}U_\beta}{2} - 0.5U_\alpha\right) * 2\right] + \left[\left(\frac{\sqrt{3}U_\beta}{2} - 0.5U_\alpha\right) * 4\right] \quad (10)$$

Note that positive values of U_α and U_β are only taken,

$$X = \frac{\sqrt{3}U_\beta * T}{V_{dc}} \quad (11)$$

$$Y = \frac{\left[\frac{\sqrt{3}U_\beta}{2} + 1.5U_\alpha\right] * T}{V_{dc}} \quad (12)$$

$$Z = \frac{\left[\frac{\sqrt{3}U_\beta}{2} - 1.5U_\alpha\right] * T}{V_{dc}} \quad (13)$$

The six active sectors are given by the equations,

$$N = 1$$
$$T_1 = \frac{Z*T}{[Z+Y]}, T_2 = \frac{Y*T}{[Z+Y]} \quad (14)$$

$$N = 2$$
$$T_1 = \frac{Y*T}{[Y-X]}, T_2 = \frac{-X*T}{[Y-X]} \quad (15)$$

$$N = 3$$
$$T_1 = \frac{-Z*T}{[X-Z]}, T_2 = \frac{X*T}{[X-Z]} \quad (16)$$

$$N = 4$$
$$T_1 = \frac{-X*T}{[Z-X]}, T_2 = \frac{Z*T}{[Z-X]} \quad (17)$$

$$N = 5$$
$$T_1 = \frac{X*T}{[X-Y]}, T_2 = \frac{-Y*T}{[X-Y]} \quad (18)$$

$$N = 6$$
$$T_1 = \frac{-Y*T}{-[Z+Y]}, T_2 = \frac{-Z*T}{-[Z+Y]} \quad (19)$$

The ON condition for the three phases is modeled as,

$$T_{aON} = [T - T_1 - T_2] * 0.25 \quad (20)$$

$$T_{bON} = T_{aON} + 0.5T_1 \quad (21)$$

$$T_{cON} = T_{bON} + 0.5T_2 \quad (22)$$

The above mentioned equations have been modeled in the SVPWM block using Simulink environment respectively.

5. SIMULATION RESULTS

Test simulations prove the efficiency of the proposed SVPWM drive system of the sensorless BLDC motor. The BLDC motor is capable of operating inbetween 12V to 310V. The PMSM with trapezoidal back EMF is considered to be a BLDC motor for both sensored and sensorless control with non- in MATLAB Simulink R2009a environment. The input parameters are estimated for the designing of the above mentioned topology in Table 1.

Table 1. Parameter Estimation

Parameter(s)	Value(s)
Supply Voltage (DC)	200 V
Switching frequency	20 KHz
Stator phase resistance	2.8750 Ω
Stator phase inductance	8.5 mH
Set Speed (N)	1200 rpm
Set Torque (T)	3 Nm

It is to be noted that BLDC motor is a closed loop motor and control of speed is mandatory for the reduction of torque ripple. As per the input set speed of 1200 rpm, the proper response of the motor in the output waveform is shown in Figure 3.

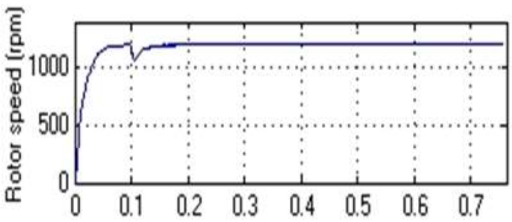

Figure 3. Speed waveform of the proposed BLDC drive

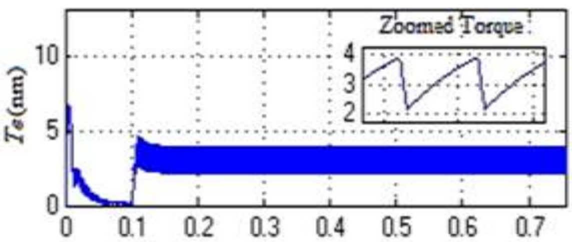

Figure 4. Proposed Sensorless Torque

The trapezoidal back EMF waveform of the closed loop three phase BLDC motor is shown in Figure 5. The non-linear stator current of the BLDC motor in the proposed topology is shown in Figure 5. In order to verify the efficiency and torque ripple suppression of the proposed topology, it is essential to compare the obtained torque waveform with a conventional method. The amount of torque ripple (in percentage) present in a BLDC motor is,

$$\text{Torque ripple (\%)} = \frac{\text{Upper peak value} - \text{Lower peak value}}{2} \qquad (23)$$

Based on Equation 23, the torque ripple (%) in conventional sensored BLDC motor is, 4.4 Nm-2.3 Nm/2 i.e. upper peak value-lower peak value/2 for a set torque of 3 Nm as in is 1.1 Nm. (approx).The torque waveform of proposed sensorless BLDC motor is shown in Figure 4. As per Equation 23, the torque ripple (%) in the proposed closed loop sensorless BLDC motor is 3.7 Nm-2.5 Nm/2 for the same set torque of 3 Nm is 0.6 Nm. Note that, the oscillations in the torque waveform of the proposed topology is quite normal for all sort of sensorless drives, since no sensors are present in the BLDC motor for better rotor position accuracy.

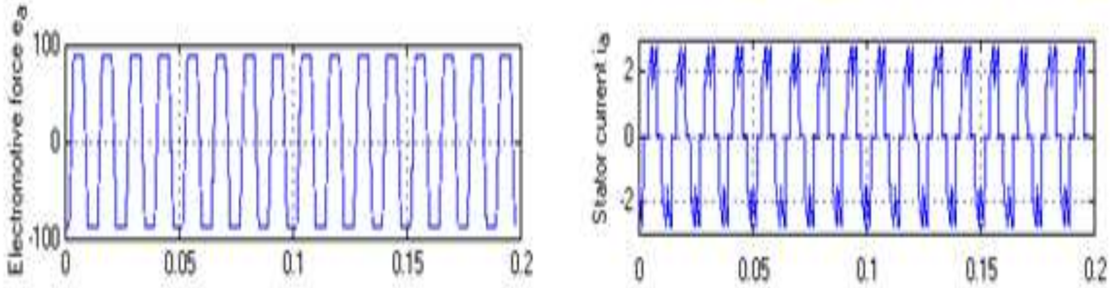

Figure 5. Stator Current and Back EMF Waveform

6. HARDWARE RESULTS

The experimental setup used for the validation of the proposed modeling of BLDC motor for sensorless operation is given in Figure 6. It consists of TI Piccolo F28035 microcontroller (MC), a 3 phases MOSFET, voltage divider circuit, current amplifier, speed and current controller and three dual gate drivers. Figure 7 show the measured expanded current of phase-A, B and C. Figure 8 shows the Back EMF of A and B Phases.

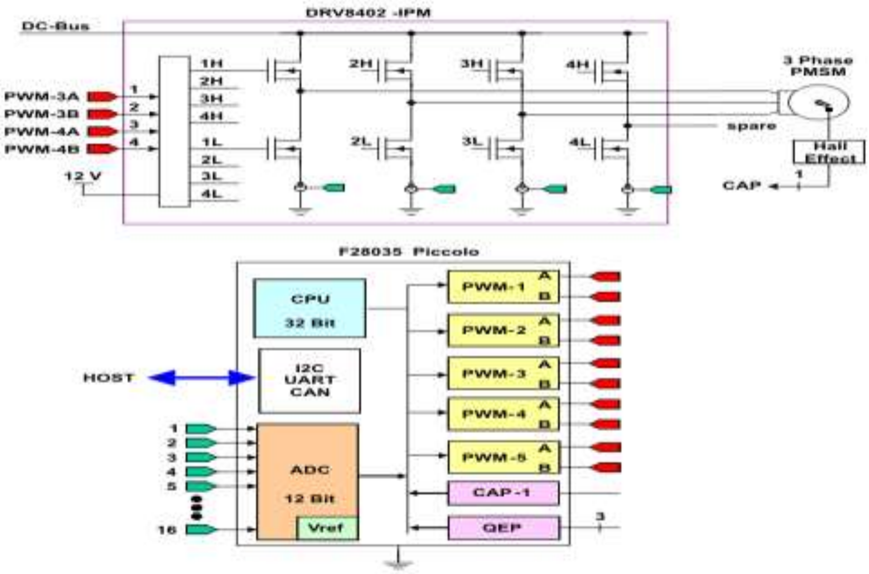

Figure 6. Proposed VSI BLDC motor drive Layout withTI Piccolo F28035 MC

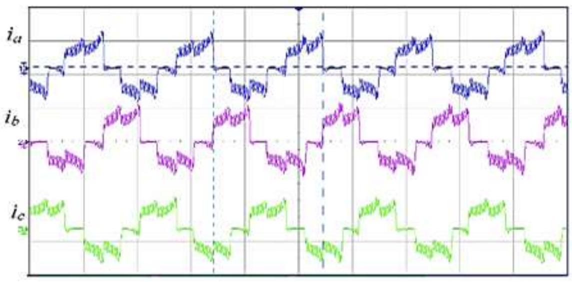

Figure 7. Phase Current Waveform -ia, ib, and ic

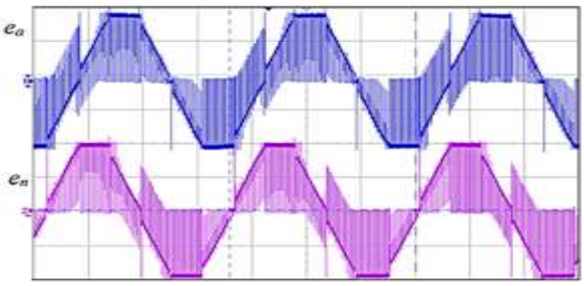

Figure 8. Shows The Back EMF of ea and ea.

7. CONCLUSION

This paper has proposed a cost effective torque ripple suppression approach using SVPWM scheme for a slim type BLDC motor. The motor can be operated in wide range of speed. The main advantage of this proposed (sensorless BLDC) topology is that torque ripple is effectively minimized about half (50% in approx), even than a sensored BLDC motor which has better efficiency and accuracy compared with sensorless BLDC motor. The result obtained fro the MATLAB Simulink environment and MC based hardware results proves the effectiveness of the proposed topology. Thus, the minimization of torque ripple in slim type sensorless BLDC motor leads to smooth operation, better performance, reduced operating temperature and improved life span respectively.

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