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PWM SWITCHING STRATEGY FOR TORQUE RIPPLE MINIMIZATION IN BLDC MOTOR

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This paper describes a new PWM switching strategy to minimize the torque ripples in BLDC motor which is based on sensored rotor position control. The scheme has been implemented using a PIC microcontroller to generate a modified Pulse Width Modulation (PWM) signals for driving power inverter bridge. The modified PWM signals are successfully applied to the next up-coming phase current such that its current rise is slightly delayed during the commutation instant. Experimental results show that the current waveforms of the modified PWM are smoother than that in conventional PWM technique. Hence, the output torque exhibits lower ripple contents.

K e y w o r d s: permanent magnet, brushless DC, modified PWM, sensored control, torque ripple

1 INTRODUCTION

In conventional DC motors with brushes, the field winding is on the stator and armature winding is on the rotor. The motor is relatively more expensive and needs maintenance due to the brushes and accumulation of the brush debris, dust, and commutator surface wear. Moreover in certain hazardous locations, the application of DC brushed motors is limited due to the arcing. This could be solved by replacing the mechanical switching components *ie* commutator and brushes by power electronic switches. Brushless DC (BLDC) motor has a permanent magnet rotor and a wound field stator, which is connected to a power electronic switching circuit.

The BLDC control drive system is based on the feedback of rotor position, which is obtained at fixed points typically every 60 electrical degrees for six-step commutations of the phase currents [1]. The BLDC motor drives have high efficiency, low maintenance, longer life span, low noise, control simplicity and compact construction. Based on the shape of the back-EMF, the brushless motors can be classified to have either trapezoidal or sinusoidal back-EMF. In a BLDC motor, the permanent magnets produce an air gap flux density distribution that is of trapezoidal shape, hence, resulting in trapezoidal back-EMF waveforms.

The torque pulsations in PM BLDC motors are generally resulted from the deviation from ideal conditions. It can be either related to the design factors of the motor or to the power inverter current excitation resulting in non-ideal current waveforms [2]. Consequently, the undesired torque pulsation in PM BLDC motor drives may lead to speed oscillations, resonances in mechanical portions of the drive causing acoustic noise and visible vibration patterns in high precision machines [3]. Therefore, the torque ripple minimization or elimination is a considerable issue in BLDC motor drives. The torque pulsations could typically be minimized by two techniques, first is by the improved motor designs and the second is by improved control scheme.

Improved motor design techniques for pulsating torque minimization include skewing, fractional-slot winding, short-pitch winding, increased number of phases, air-gap windings, adjusting stator slot opening and wedges, rotor magnetic design through magnet pole arc, width and positions. On the other hand, improved motor control schemes include adaptive control technique, preprogrammed current waveform control, selective harmonics injection techniques, estimators and observers, speed loop disturbance rejection, high speed current regulators, commutation torque minimizations and automated self-commissioning schemes [4].

Minimization of torque ripple in PWM AC drives is presented in [5] which proposed a pulse width modulation (PWM) technique for minimizing the RMS torque ripple in inverter-fed induction motor drives. Another study of PWM methods in permanent magnet brushless DC motor speed control system is given in [6]. The study compared the efficiency, reliability and torque ripples of six PWM methods implemented in voltage inverter PM brushless motor drives.

A PWM control algorithm for eliminating torque ripple caused by stator magnetic field jump of brushless DC motors is proposed by [7]. Reference [8] proposed a PWM chopping method to improve the torque ripple for brushless DC miniature motors. The comparison of two types of switching strategies studied to reduce the torque ripple shows that the PWM chopping method has a higher output torque and lower ripples comparing to the overlapping method. Reference [9] discussed the influences of PWM

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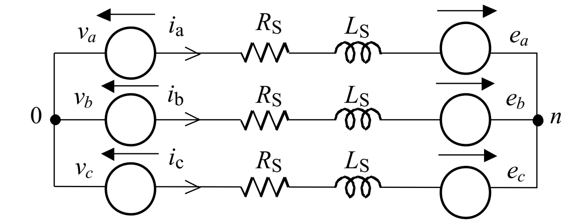

Fig. 1. Brushless DC motor equivalent circuit

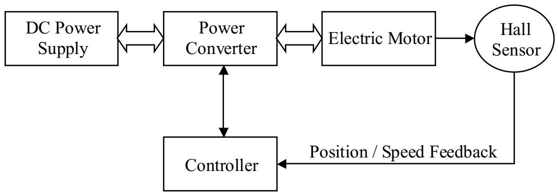

Fig. 2. BLDC drive system components

mode on the current generated by back-EMF of switch-off phase in BLDC motor. A low cost digital control technique is proposed in [10] with a constant frequency digital PWM controller, simulated and experimentally verified for a BLDC motor drive system.

In [11], commutation torque ripple reduction in BLDC motor using PWM_ON_PWM mode. Reference [12] presents a new method on reducing commutation torque ripples generated in brushless DC motor drives based on Commutation Time Control.

As mentioned above, these were several research works in the past decade which focused on minimizing torque ripples during commutation time. However, in this paper, a modified PWM signal is applied during the start-up of the commutation sequence for the incoming phase current such that it will gradually build up and reach the targeted value in order to minimize the torque ripples in BLDC motor drives. The proposed method does not require any additional hardware modification.

2 MATHEMATICAL MODEL OF BLDC MOTOR DRIVE SYSTEM

BLDC motor produces a trapezoidal back-EMF, and therefore the excited current waveform is preferably rectangular-shaped. The phase resistances of the stator windings are assumed to be equal. The self and mutual inductances are constant irrespectively of rotor position due to surface mounted permanent magnet rotor topology. The rotor-induced currents are neglected and the damper windings are also not present. The three phase voltage equation can be expressed as in equation (1), [13].

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where

R_s : phase resistance, v_{an}, v_{bn}, v_{cn} : phase voltages,
L_s : self-inductance, i_a, i_b, i_c : phase currents,
M : mutual inductance, e_a, e_b, e_c : phase back-EMFs.

The equivalent circuit for the BLDC motor is shown in Fig. 1.

Due to the interaction of the currents in stator windings and the magnetic field from rotor magnets, the electromagnetic torque of BLDC motor is produced as follows

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (2)$$

where ω_m is the mechanical speed of the rotor. The equation of motion is given by

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = \frac{T_e - T_L - B\omega_m}{J} \quad (3)$$

where

T_L : load torque,
B : damping constant,
J : moment of inertia of rotor shaft and load [14].

BLDC drive system typically consists of BLDC motor, power electronics converter, hall-effect sensors and controller as shown in Fig. 2.

For six-step motor control, at each step the instantaneous output power will be will be deliver from two phases connected in series, and is given by

$$P_o = \omega_m T_e = 2EI \quad (4)$$

where I is the current amplitude and E is the induced back-EMF. From equations (2) and (4), the output torque can also be expressed as

$$T_e = 2k\phi I = 2k_t I \quad (5)$$

where k_t is the motor torque constant.

3 ANALYSIS OF BLDC TORQUE RIPPLES MOTORS DUE CURRENT COMMUTATION

In order to minimize the torque ripples in Brushless DC machines the analysis of torque curves to be performed. The constant current torque waveforms depend on many parameters in which relating to design parameters [15].

The common used commutation in 3 phase BLDC motor is the six-step, in which each phase voltage is energized for interval of 120 degree electrical according to the rotor electrical position. At any sector, only one phase is energized as positive and one of the other phases is energized

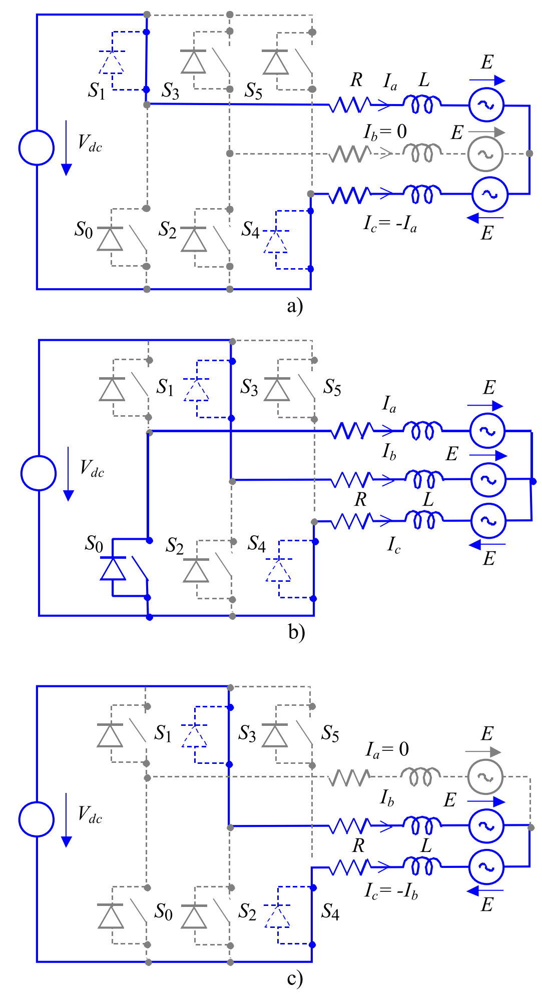

Fig. 3. Transition of conduction from phase A to B (a) Phase A conducts, (b) During commutation time between phase A,B, (c) Phase B conducts

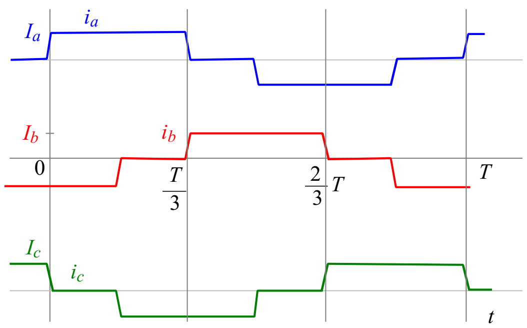

Fig. 4. Ideal current waveform of 3-phase BLDC Motor

as negative in order to maintain a current path. For control the BLDC motor a typical 3 phase full bridge will be used for drive the motor.

For the analysis of commutation time, the commutation of the current through two phases to be considered, one phase will be switched off, the second phase will replace the switched off phase and the third phase will remained conducting.

In this analysis the commutation from phase A to phase B will be considered. The current transfer happens during the six-step, since there is one phase to be switched ON while other switch will be OFF, and the third phase switch will remain conducting. In this analysis the transition of conduction from Phase $A(+)/C(-)$ to $B(+)/C(-)$ will be considered as shown in Fig. 3. In this case the phase A is the de-energized phase and phase B will be the in-coming energized phase and phase C is the conducting phase.

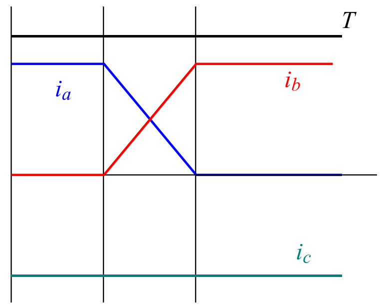

Fig. 5. Ideal current commutation in BLDC motors

Ideally the current in BLDC motor with trapezoidal back-EMF is square in shape. Figure 4 shows the ideal current waveforms, yet practically the current in the upcoming phase takes a finite time to settle to its maximum value, also the die-off phase takes a finite time to get vanishes to zero. This period of commutation between any pair of phases is relatively short comparing to the period of phase conduction.

At each 60 electrical degree, there will be 2 switches conducting, one from high side of the phase and the other will be from the low side. When phase A and C conducting the high side switch S1 and the low side S4 will be in ON state and current will start build up. Yet, when switch S1 turned OFF, the current will decayed through the freewheeling diode D0 and the switch S4, this will take a short time which will occur at each step. In the next sequence where phase B high-side with phase C low- side, the switches S1 and S4 will be in ON state.

4 PROPOSED METHOD FOR TORQUE RIPPLE MINIMIZATION

The commutation between the 3 phases occurred six times per electrical revolution. As a result current ripple generated in commutation period which is the main drawback of BLDC Motor.

In the conduction region, 2-phases are conducted based on the position of rotor, the rotor position is usually sensed by Hall sensors. The Hall sensors generate three signals corresponding to six states of rotor position. On the other hand commutation region is to be transient region which converts from the current conduction from one phase into the next one, commutation is relatively shorter than conduction region, and 3-phases (rising phase, decaying phase, and conducting phase) are all conducted.

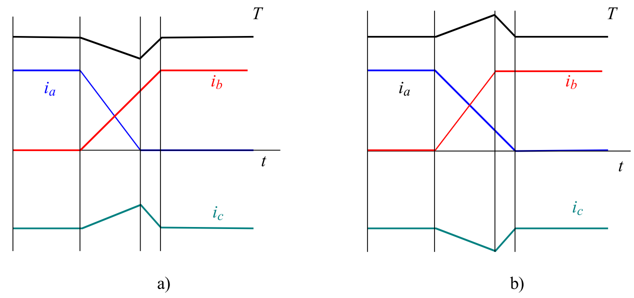

Fig. 6. Phase currents and torque during commutation event

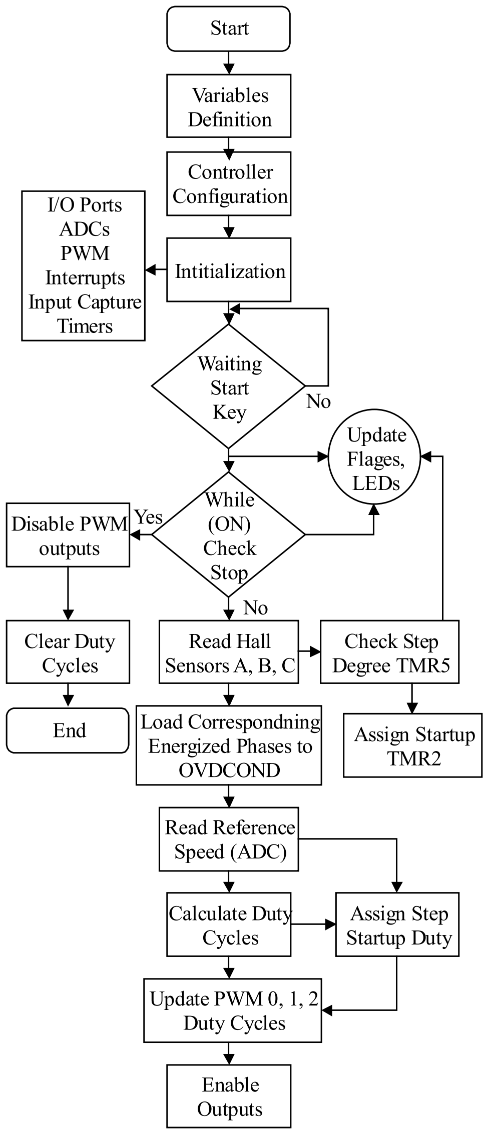

Fig. 7. Flow chart of modified PWM signals

Conduction and commutation appears six times per one electrical rotation of the rotor [16]. The current waveform during commutation is shown as in Fig. 5.

In practice, the rate of current rise is mismatched with the rate of the current decay which produces torque ripples. The torque ripples are critical issue in BLDC drives; hence a lot of techniques has been introduced to minimize the torque ripples. In this paper, a proposed technique used to minimize the torque ripples in BLDC motors will be discussed and analyzed from the perspective of motor control side.

Based on the commutation events as shown in Fig. 6 (a), the modified PWM has been implemented by the micro-controller will be applied speed-up the energized phase current during high-speed region. In this case, the current in the outgoing phase (phase A) would reach zero before the current in in- coming phase (phase B) reaches its max value. The current rates of change can be given by

$$\frac{\mathrm{d}i_a}{\mathrm{d}t} > \frac{\mathrm{d}i_b}{\mathrm{d}t}\,. \tag{6}$$

Therefore, the instantaneous phase C current will peak up slightly during this commutation time as shown in Fig. 6 (a). On the other hand, phase A current decay time could also be possibly slower than phase B current rise time. Because of this mismatch of decay rate of phase A current i_a and rise rate of phase B current i_b, small current dip appears in phase C current. Consequently, the net torque will exhibit torque spike during the commutation instances. The current rates of change are given by

$$\frac{\mathrm{d}i_a}{\mathrm{d}t} < \frac{\mathrm{d}i_b}{\mathrm{d}t}\,. \tag{7}$$

The proposed PWM scheme will slow-down the energized phase current during low-speed region so that it will minimize the associated torque ripple which appear during the commutation interval.

Referring to the two current loops during commutation, which is the diode loop and the switch loop. By assuming constant back-EMF and ignoring the phase resistance, then the phase currents rate of change During commutation can be expressed as

$$\frac{\mathrm{d}i_a}{\mathrm{d}t} = -\frac{V_{dc} + 2E}{3L_s}\,, \tag{8}$$

$$\frac{\mathrm{d}i_b}{\mathrm{d}t} = -\frac{2(V_{dc} - E)}{3L_s}\,, \tag{9}$$

$$\frac{\mathrm{d}i_c}{\mathrm{d}t} = -\frac{V_{dc} - 4E}{3L_s}\,, \tag{10}$$

where Vdc is the dc link voltage. The time taken for i_a to die-off from its value I to zero will be

$$t_f = \frac{3L_s I}{V_{dc} + 2E}\,. \tag{11}$$

The time i_b to build up from zero to its final value I:

$$t_r = \frac{3L_s I}{2(V_{dc} - E)}\,. \tag{12}$$

Considering the case of $t_f = t_r$, which described in Fig. 5 where the fall time and rise time are equal, this case could

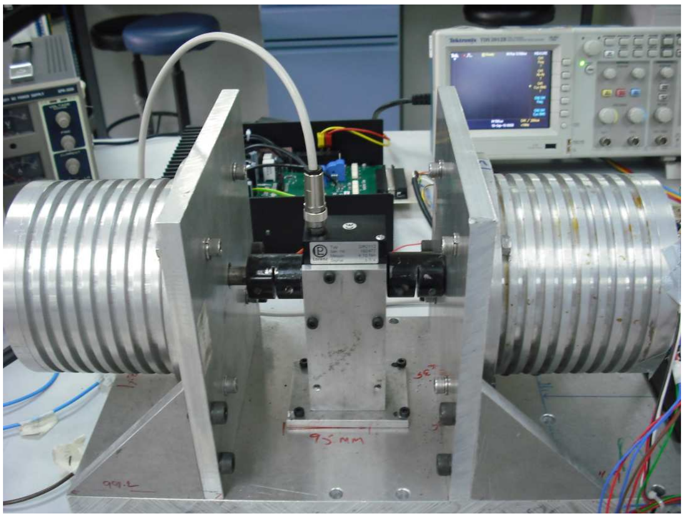

Fig. 8. Experimental test bench

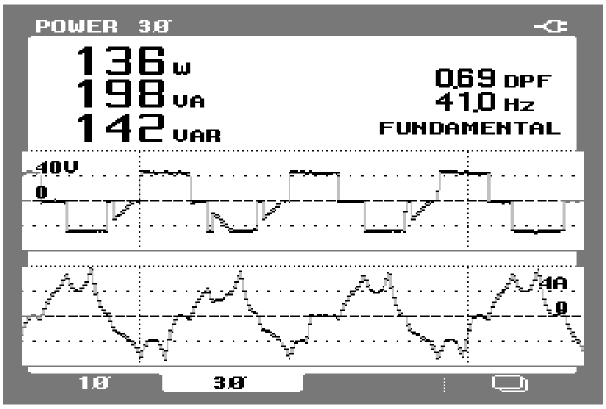

Fig. 9. Normal PWM control motor current and line voltage

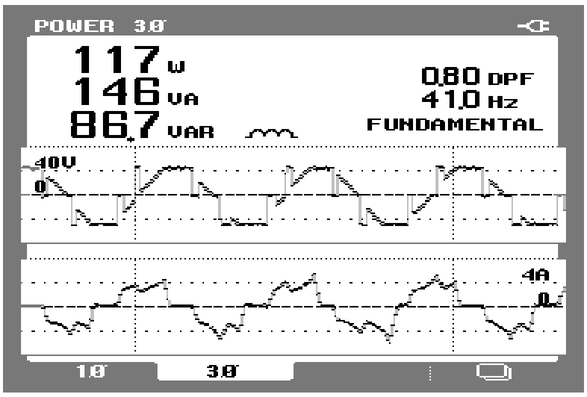

Fig. 10. Modified PWM control motor current and line voltage

happen when dc link voltage (V_{dc}) equal to 4 times of the induced back-EMF (E).

$$t_r\big|_{V_{dc}=4E} = \frac{3L_sI}{2(V_{dc}-E)} = \frac{3L_sI}{2(4E-E)} = \frac{L_sI}{2E}\,, \quad (13)$$

$$t_f\big|_{V_{dc}=4E} = \frac{L_sI}{2E}\,. \quad (14)$$

And this will be considered as the average commutation time between two phases. The total conduction time of phase current will be $t_{total} = \frac{T}{3}$

$$t_{total} = t_r + t_{\rm cond}\,. \quad (15)$$

From this, the conduction time of the phase will be

$$t_{\rm cond} = \frac{T}{3} - \frac{L_sI}{2E}\,. \quad (16)$$

The proposed method will be based on applying the modified PWM at the interval whereas it proportional to the value of step time to the value of commutation time ratio. The commutation time in much smaller if compared with the total phase conduction time. Figure 7 describes the flow chart used to generate the modified PWM signals implemented in the PIC microcontroller.

As can clearly be seen from Fig. 7, "Assign Step Startup Duty" block will be used to gradually delay the build-up of current in the in-coming phase at low speed region or speed-up current rate in high-speed region. This will result in overcoming the tips and dips occurred during phase current commutation. This is achieved via the modified PWM signals preprogrammed to execute only during the commutation instants.

5 RESULTS

Figure 8 shows the experimental test bench, where the tested motor has been coupled with the torque Lorenz sensor, and the other end of the sensor is coupled to a PM generator.

Figure 9 shows the output current and the line voltage using the normal PWM control. While the waveforms shown in Fig. 10 show the output current and line voltage of the BLDC motor under the modified PWM control technique.

The waveform shown in Fig. 9, illustrates the phase current of brushless DC motor using conventional PWM switching. Comparing with the waveform of the modified PWM switching shown in Fig. 10, it clearly shows that the ripple in current waveform is minimized, thus it will result in smother output torque with a minimum torque ripples.

Figure 11 shows a comparison of the generated output torque using both types of control. It is obvious that by adopting the modified PWM technique will produce a smoother output torque; result in a visible reduction of the torque ripples.

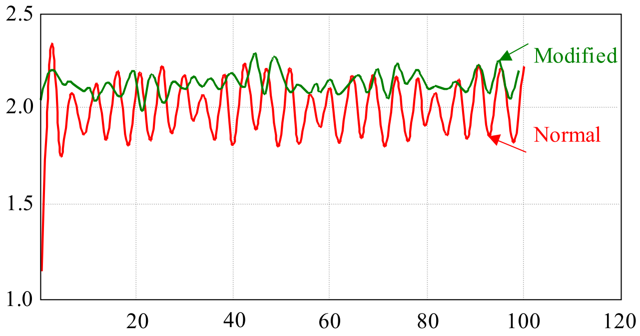

Fig. 11. Motor output torque at 41 Hz

6 CONCLUSION

The modified Pulse Width Modulation (PWM) signals for driving the power inverter bridge for BLDC motor drives have been successfully implemented using PIC microcontroller. The BLDC motor control based on rotor position sensing scheme been discussed. It can clearly be seen from the measured results of phase currents that the modified PWM signals has managed to reduce the current spike and dips, hence resulting in lower torque ripples.

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