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Torque Ripple Minimization in BLDC Drive Using PWM_ON_PWM Scheme

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Abstract:
In this paper a detailed analysis on torque ripples of brushless dc drives in both commutation and conduction region is given. A new control strategy for the elimination of torque ripples in BLDC motor by employing PWM_ON _PWM scheme has been introduced. PWM_ON_PWM strategy is mainly applied to compensate the commutation torque ripples during the commutation period caused by commutation current and it cannot entirely remove the torque ripples that are resulted from current introducing at the turn off phase. The duty cycle of PWM is regulated for achieving closed loop operation and simulation results are used for revealing circuit validation.

Keywords: *BLDC Motor, Electro Magnetic Force (EMF), electromagnetictorqueripple, PWM_ON_PWM*

1. Introduction

Brushless DC motors having 120˚ flat top back-EMF has several merits as comparing with other permanent magnet motors. BLDC motors have some unique features as they are highly reliable with low maintenance and high torque-speed ratio. The major disadvantage of BLDC motor is the torque ripple resulted in conduction as well as in commutation region, however which deteriorates the precision of BLDC drive.

Torque ripple reductions have been the focus of recent days and the ongoing experimental works are concentrated on commutation torque ripple and the torque ripple produced as a result of diode freewheeling of non-conducting phase. In [4] for the commutation ripple, torque is related to current and varies with speed. In reference [5], a step down converter is inserted to control dc-link voltage to decrease the commutation torque ripple, but the bandwidth of the converter was not taken into consideration, hence it satisfies torque pulsation at low speed only. In [7], a SEPIC based circuit is used, but this structure has to add three switches and their respective inductances, capacitances, and diodes.

In [8] and [9] for the diode freewheeling of non conducting phase, several modulation schemes have been analyzed, the PWM_ON_PWM and PWM_PWM methods are considered, that deteriorates the diode freewheeling of non conducting phase. PWM_ON_PWM is an efficient modulation pattern by considering the power dissipation. PI controller is one of the effective speed controllers which give the accurate speed.

Torque ripple is one of the major problems and one of the methods to resolve this problem is to apply the motor’s back EMF waveforms function to regulate current. In [11] a torque method for minimizing the torque ripple of BLDC motor with non-ideal back EMF, but the diode freewheeling of the non conducting phase was not under consideration and the modulation scheme employed is PWM_PWM.

This paper introducing a neoteric method for the minimization of torque ripples in BLDC motor. In this method closed loop operation of BLDC motor and the modulation scheme for the inverter is PWM_ON_PWM, which is used for removing the diode freewheeling of inactive phase. Simulation results showed that, compared with the conventional PWM_ON method, the new methodology which can decrease the torque ripples in a very effective manner.

2. BLDC Motor Modelling

BLDC motor has three stator windings and the rotor consist of permanent magnets. The three phase BLDC motor is star connected which is fed by a conventional three phase voltage source inverter. Its configuration is given in Fig.1, where the phase voltages are Va,Vb,Vc, and the phase currents are ia, ib, ic and the phase back-EMF are e_a, e_b, e_c, R is the phase resistance and L is the self inductance of each phase. The voltage equations of three phase windings with phase variables are as given below:-

$$V_A = Ri_a + L\frac{di_a}{dt} + e_a + U_N \quad (1)$$

$$V_B = Ri_b + L\frac{di_b}{dt} + e_b + U_N \quad (2)$$

$$V_C = Ri_C + L\frac{di_C}{dt} + e_C + U_N \quad (3)$$

And hence the expression for the electromagnetic torque can be written as:

$$Te = (\frac{e_a i_a + e_b i_b + e_c i_c}{\omega}) \quad (4)$$

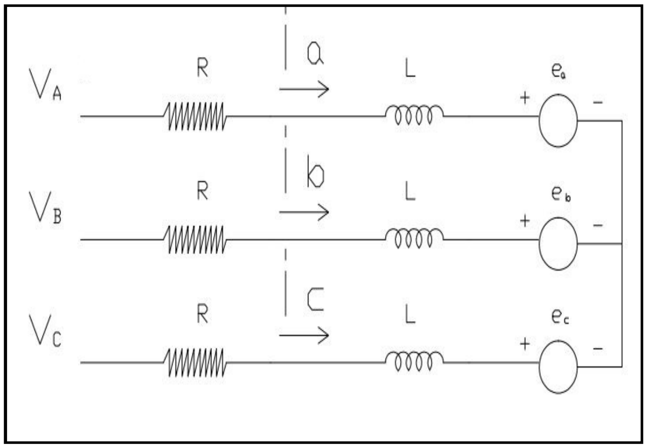

Figure 1: BLDC motor - Equivalent circuit

where T_e is the electromagnetic torque and ω is the mechanical velocity of the motor. The relation of three phase current in BLDC motor is

$$i_a + i_b + i_c = 0 \quad (5)$$

3. Operation of Proposed System

A BLDC motor has mainly two operating states: conduction state and commutation state. In the conduction state with selected rotor position, two phases are conducted. In the case of commutation state which is a transient area that converts current conduction in to next one and at that time three phases will conduct i.e. rising, decaying and non commutation phase.

The neoteric proposed circuit comprises of an inverter which is used to develop a three phase rectangular current with a pulse width of 120˚. Fig 2 shows the proposed circuit.

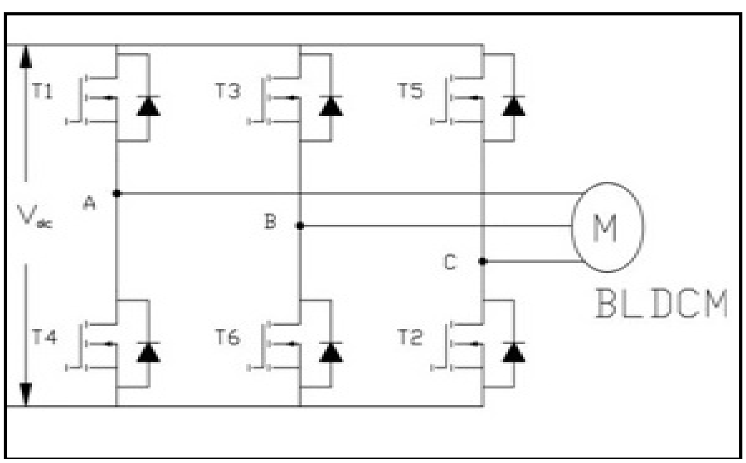

Figure 2: The new proposed circuit configuration

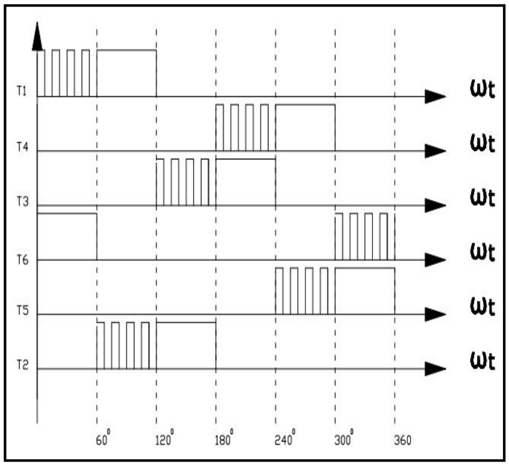

Figure 3 (a): PWM_ON modulation pattern

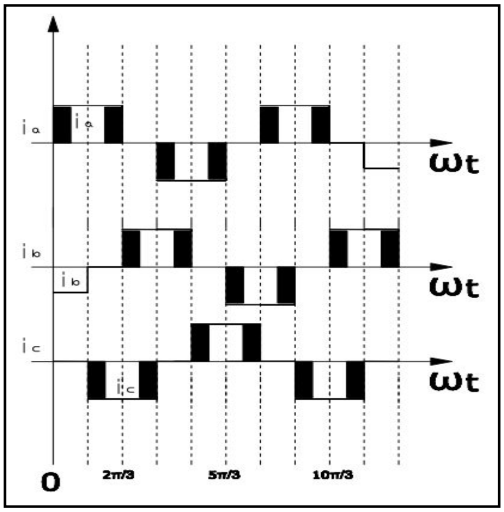

Figure 3 (b): PWM_ON_PWM pattern

Fig.3 shows the conventional and new PWM patters in BLDC switching scheme. The back emf of every phase winding is trapezoidal and its 120˚ flat-top amplitude is equal to E_m.. For example consider the region from π/2 to 2π/3, during commutation the condition satisfied is given below:-

$$e_a = e_b = -e_c = -Em \qquad (6)$$

Assume ω be the mechanical velocity of the rotor, at that time the torque obtained is described as

$$Te = \left(\frac{e_a i_a + e_b i_b + e_c i_c}{\omega}\right) = \frac{2E_m i_c}{\omega}$$

From (7) it is clear the non-commutation phase current during commutation is in proportional to the electromagnetic torque, i.e. it is possible to reduce the commutation torque ripple effectively by keeping the non-commutation phase current constant during commutation,

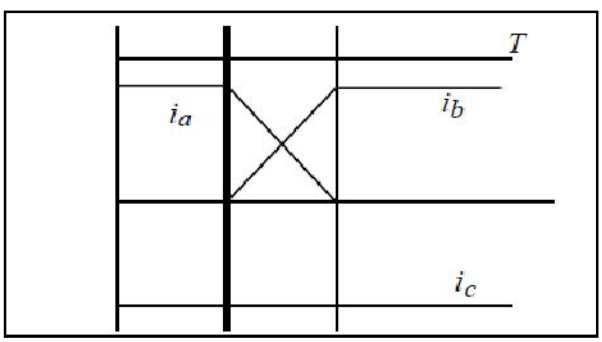

Figure 4: BLDC motor - Ideal current commutation

4. Commutation without Considering PWM Modulation Scheme

Considering a particular commutation process at 2π/3,at that time phase A current flows through the diode across the mosfet T_4 and decays to zero slowly, while phase B current raises slowly and finally attains the steady-state value. By analysing the circuit equation during commutation without considering the PWM modulation scheme may be explained as follows.

$V_A - V_C = 0$ (8)

$V_B - V_C = U_d$ (9)

Comparing the time constant L/R of a BLDC drive, PWM period can be so small and hence the winding resistant can be avoided. Here the steady state phase current value is taken as I_o before and after commutation. Phase currents during commutation can be derived as

$$i_a = I_O - \frac{U_d + 2E_m}{3L} t$$

$$i_b = \frac{2(U_d - E_m)}{3L} t \qquad (10)$$

$$i_c = -I_O - \frac{U_d - 4E_m}{3L} t$$

Hence the electromagnetic torque during the commutation can be explained as

$$T_e = (I_O + \frac{U_d - 4E_m}{3L} t)\frac{2E_m}{\omega} \qquad (11)$$

From (11) the turn-off time of phase A and phase B during the commutation are

$$T_{(A)} = \frac{3LI_O}{Ud + 2E_m} \qquad (12)$$

$$T_{(B)} = \frac{3LI_O}{2(U_d - E_m)} \qquad (13)$$

From (10) to (13) it is clear that commutation between two phases cannot be completed in the same time schedule. It is possible to occur three cases

- Case 1: If U_d greater than E_m , i.e. the case of motor speed is less than a critical value, the commutation between two phases cannot be completed in the same moment and hence i_b reaches it steady state value before i_a falls to zero and shown in fig.5(1)
- Case 2: If U_d is equal to E_m , i.e. the turn off between the two phases can be completed at the same moment. If it happens motor runs at a certain speed, and hence i_b reaches it steady state value just as i_a falls to zero and is shown in fig.5(11).At that time torque became equal to as per eqn(7)
- Case 3: If U_d less than E_m ,the turn off between two phases cannot be completed in the same time that is the motor speed is greater than a critical level, and hence i_b does not reach its steady state value when i_a falls to zero and is shown in fig.5(111)

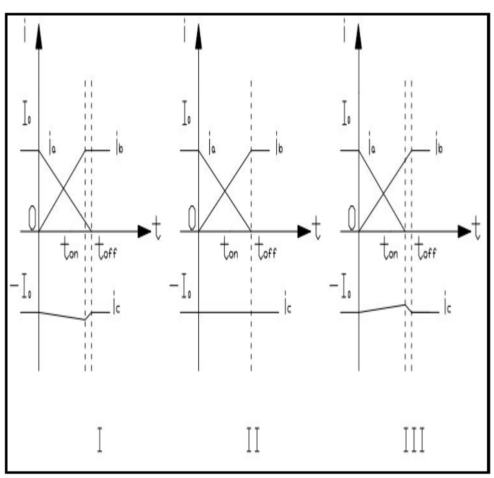

Figure 5: Three cases of commutation

5. Torque Ripple Reduction Using Proposed Scheme

In the proposed scheme mainly two methods are opted for reducing torque ripples in BLDC motor. First one is to provide gate pulses to the inverter section by using PWM_ON_PWM scheme. It is a bilateral pattern in which PWM mode is applied on the first and last

30˚ while maintaining a constant turn on mode in the remaining middle 60˚. By this way it will compensate the torque ripples induced by the commutation current during commutation region.

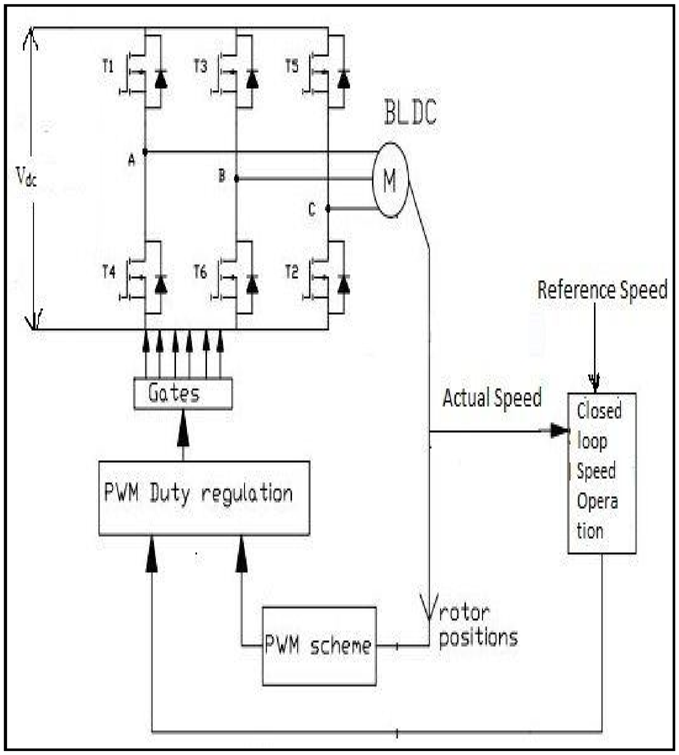

Figure 5: Block diagram of proposed BLDC dive system

5.1. Analysis at Commutation Period

Mainly torque ripples are occurred due to commutation. The analysis during the commutation process as follows

For analysis overlapping commutation is introduced which restrained the commutation torque ripple through the duty cycle of PWM .Considering a commutation process at the time of current shifting from phase A to B , T_1 is switched OFF and T_2 is switched ON, T_3 is chopping. For analysis overlapping commutation is proposed which restrained the commutation torque ripple through the duty cycle of PWM. So the phase voltage equations are as follows:-

$$V_A = D \times u_d = Ri_a + L\frac{di_a}{dt} + e_a + U_N \quad V_B = u_d = Ri_b + L\frac{di_b}{dt} + e_b + U_N \quad (14) \qquad V_C = (1-D)\ u_d = Ri_c + L\frac{di_c}{dt} + e_c$$

From the above thee equations, the neutral voltage can be obtained as

$$U_N = \frac{2u_d - e_a - e_b - e_c}{3} \qquad (15)$$

where D corresponds to the switching function and D=1 and D=0 shows switching ON and OFF respectively.

considering the carrier cycle of PWM, D maintains 1 during DT and 0 during (1-D)T where D is the duty ratio of PWM.

Substituting (15) in (14), the differential equations of phase current is explained as

$$L\frac{di_a}{dt} = D \times u_d - e_a - U_N = \frac{(3D - 2)u_d + e_a + e_c - 2e_a}{3} = V_{a1} \qquad (16)$$

$$Ri_b + L\frac{di_b}{dt} = u_d - e_b - U_N = \frac{u_d + e_a + e_c - 2e_b}{3} = V_{b1} \qquad (17)$$

By considering the initial conditions $i_a(t=0)=I, i_b(t=0)=0$ $ic(t=0) = -I$

$$i_a = \frac{u_{a1}}{R} + (I - \frac{V_{a1}}{R})e^{-(\frac{R}{L})t} \qquad (18)$$

$$i_b = \frac{V_{b1}}{R} - \frac{V_{b1}}{R} e^{-(\frac{R}{L})t} \quad (19)$$

First term can be described as $e^{-(\frac{R}{L})t} = 1 - (\frac{R}{L})t$ and putting it in to (18) and (19) the time t_a when i_a reduces from 1 to 0 and the time t_b when i_b increases from 0 to 1 can be explained as

$$t_a = \frac{3IL}{2e_a - e_b - e_c + (3D - 2) \times u_d} \quad (20)$$

$$t_b = \frac{3IL}{u_d + e_a + e_c - 2e_b} \quad (21)$$

So the duty cycle of PWM can be written as

$$D(k) = 1 - \frac{e_a(k) + e_b(k) - 2e_c(k)}{3u_d} \quad (22)$$

The duty ratio given in equation (22) is used for providing gate pulses to the inverter switches.

6. Simulation Results

The proposed BLDC drive system is simulated with the aid of MATLAB/SIMULINK. Parameters of BLDC motor are shown in the Table I. Simulation results for the introduced BLDC drive are explained here. The performance of the drive is based on the correct commutation of the inverter switches. In the simulation analysis, mainly conventional PWM_ON_PWM scheme and the new proposed closed loop operation with PWM_ON_PWM scheme is compared.

Parameters	**Rating**
V_{dc}	180
Inductance, L	8.5Mh
Resistance, R	2.87 ohm
Back emf Constant, k_b	.146v/rad/s
Torque Constant, K_t	1.4Nm/A
Motor Inertia, J	1.8kgcm2
Number of Poles, P	4

Table 1: Parameters of BLDC Motor

In the simulation of bldc drive, PWM_ON_PWM scheme is used. For the generation of the PWM mode back emf signals e_a, e_b, e_c and currents i_a, i_b, i_c are used.Fig.6 shows the PWM_ON_PWM mode waveform. Simulation results show the feasibility of new control scheme. For analyzing the torque ripple compensation of bldc motor with closed loop operation using PWM_ON_PWM scheme, it is necessary to compare it with a conventional method

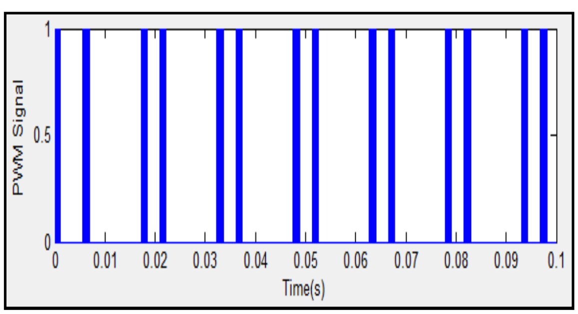

Figure 6: PWM_ON_PWM Pattern

A 2 Nm load is applied .05s and the performance is analyzed for reference speed. Speed response and torque responses for 2Nm load is shown in fig.7.Back-EMF and stator current waveforms are given in Fig 8.Also, when loaded, machine is capable of supplying the required load torque demand. For different speed and toque references, performance of the drive is evaluated and is found to be satisfactory. The results clearly indicate the feasibility of the proposed method.

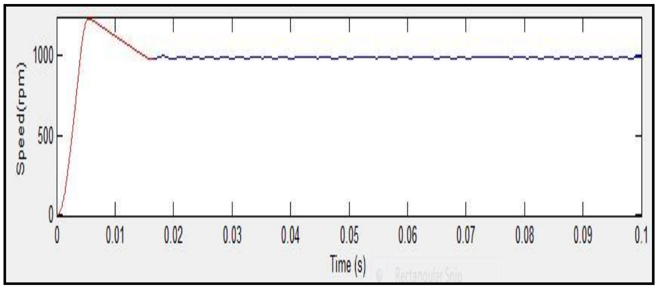

Figure 7 (a)

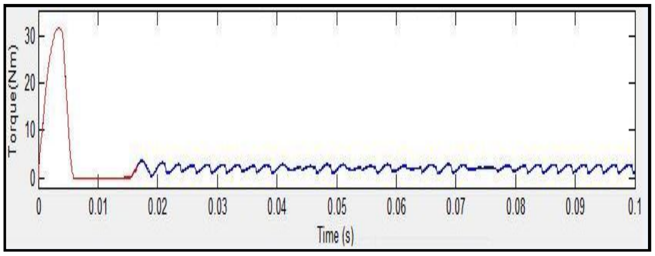

Figure 7(b): Speed and torque response using proposed scheme

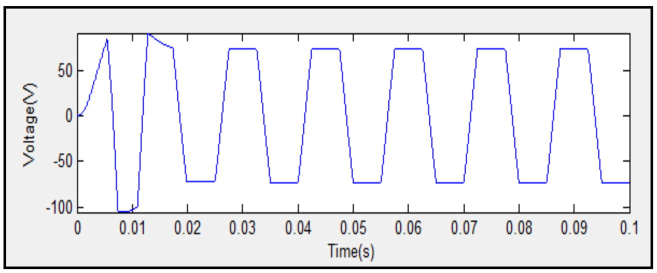

Figure 8 (a)

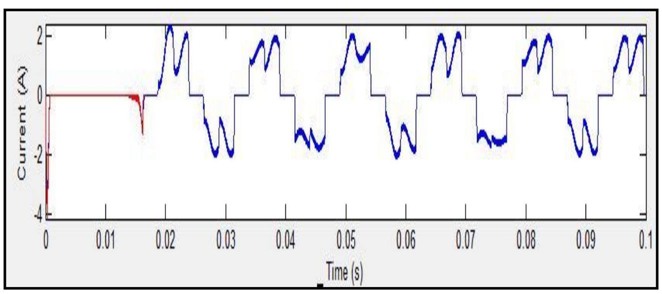

Figure 8(b): Back-EMF and Stator current using proposed scheme

From fig.8 (b) it is clear that by using new control strategy, i.e., PWM ON PWM scheme, entirely eliminate the torque ripple resulted by the commutation current in the commutation region.

In order to compare the performance of a proposed control scheme with open loop PWM_ON_PWM scheme, conventional control scheme is simulated.The simulation results are done for the same parameters.

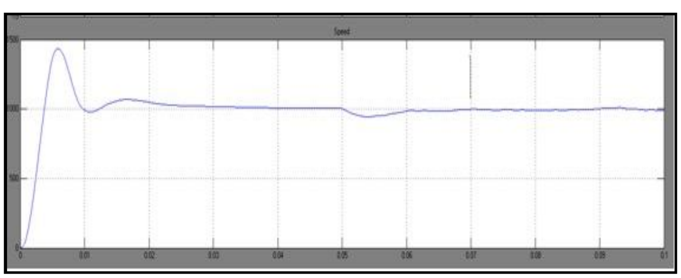

Figure 9 (a)

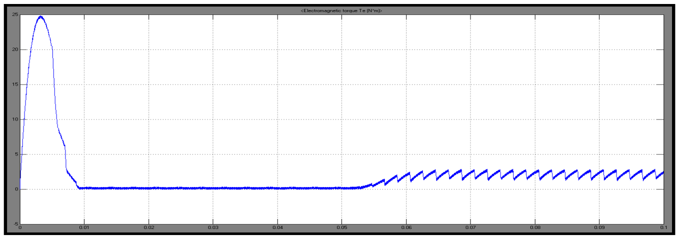

Figure 9(b): Speed and torque response using conventional scheme

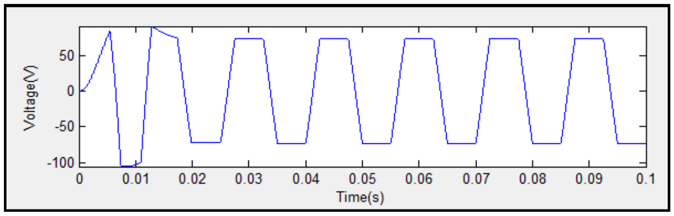

Figure 10 (a)

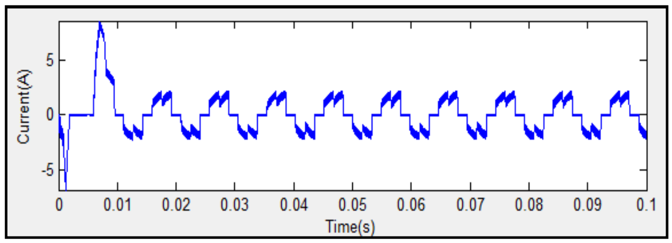

Figure 10(b): Back-EMF and Stator current using conventional scheme

Fig.8(b) shows that commutation torque ripples occurred during commutation period can be compensated by using the introduced PWM_ON_PWM method as compared with fig.10(b) using conventional PWM_ON scheme.

7. Conclusion

A BLDC drive based on PWM_ON_PWM scheme has been introduced in this paper. For switching of inverter PWM_ON _PWM scheme is used. In the analysis it is clear that PWM_ON_PWM strategy compensates the commutation torque ripples during commutation period caused by commutation current and slightly reduces the ripples during the conduction period also. Simulation results clearly show the feasibility of new control scheme.

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