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A New Torque Control Method for Torque Ripple Suppression in BLDC Motor With Nonideal Back EMF

YANDAMURI HARIBABU ***AND*** **V.V. NARASIMHA MURTHY**
Department of Electrical and Electronics Engineering, University College of Engineering Kakinada, JNTUK, AP

Abstract — *To improve the accuracy of speed and stabilization of the brushless direct current motor, a comprehensive analysis for the reason of electromagnetic torque ripples of BLDC motor with nonideal back electromotive force (EMF) drives in both the commutation and conduction regions is presented. A new automatic torque control method with a current control rule to control phase current is proposed. A new pulse width modulation technique "PWM_ON_PWM" scheme, which eliminates the diode freewheeling of inactive phase will be designed. The duty cycle of this PWM is regulated by measuring the wave function of back EMF. PI controller is used for speed regulation. Simulation results are given to show the comparison between HIGH_PWM_L_ON scheme and proposed PWM_ON_PWM scheme, the proposed method can reduce the torque ripple effectively and improve the stabilization and speed precision as well.*

Index Terms —Brushless direct current (BLDC) motors, electromagnetic torque ripple, nonideal back electromotive force (EMF), proportional integral (PI), double gimbal magnetically suspended control moment gyro (DGMSCMG), pulse width modulation (PWM).

INTRODUCTION

Brushless direct current (BLDC) motor have characteristics of high reliability, simple frame, and small friction. By comparing with PMSM, BLDC motor has the advantage of high speed adjusting performance and power density Ease of control, low rotor inertia, lowest total system cost for basic motion - Wound field motors exhibit high starting torque, series wound and can run with AC or DC. So, the BLDC motor became ideal choice for the applications like control moment gyro (CMG)'s gimbal system. which is considered to be one of the primary actuator used for the attitude control of large spacecrafts. Magnetically suspended control moment gyro (MSCMG) has the advantage of high precision and longevity owing to the zero friction and enhanced damping of high-speed rotor. Therefore, its application in the high precision servo system is restricted due to the electromagnetic torque ripple [4]. The torque ripple reduction and the control performance improvement of BLDC have been the research hotspot in years, and the main research works are focused on commutation torque ripple, the torque ripple produced by diode freewheeling of inactive phase, and the torque ripple caused by the nonideal back electromotive force (EMF) and also with irregular speed at the starting of the motor. For the commutation torque ripple, Calson *et* al. proposed that relative torque is related to current and varies with speed [5]. In [4], a single dc current sensor and an adaptive phase-change point regulation scheme should be used to suppress the commutation torque ripple, but the diode freewheeling of inactive phase was not considered. Chuang et *al.* have analyzed the influences of different pulse width modulation (PWM) strategies i.e 8 strategies on the commutation torque ripple according to the BLDC motors with unbalanced hall sensors, Speed filter is used to regulate the phase-change point automatically. However, this control method is more competent under the high-speed working condition. In [7], the reasons of commutation torque ripple for low and high speed are analyzed. In order to keep incoming and outgoing phase currents changing at the same rate during commutation, the duty was regulated at low speed and the dead beat current control was adopted at high speed, but the nonideal back EMF was not considered in this method. It is an effective way to propose some topology circuit for BLDC motor drives to control their dc-link voltage, as shown by some researchers presented in [8] - [10]. In reference [8], a buck converter is used to regulate dc-link voltage to reduce the commutation torque ripple, but the bandwidth of buck converter was not considered, so this structure can only satisfy torque pulsation at low speed. Chen *et* at. Proposed a superlift Luo topology circuit to produce desired dc-lick voltage [9], but this structure is more complex and competent only under high-speed condition. In [10], a SEPIC topology circuit is employed, but this topology structure needs to add three switches and their corresponding inductances, capacitances, and diodes. In [11] and [12] the diode freewheeling of inactive phase, various modulation methods have been analyzed, the PWM_ON_PWM and PWM_PWM methods are considered, which can eliminate the diode freewheeling of inactive phase. Considering the power dissipation PWM_ON_PWM is the better modulation method. PI speed controller is most effective speed controller which gives accurate speed.

In view of torque ripples of BLDC motor with nonideal back EMF, there are mainly two kinds of resolvents. One is to employ direct torque control to regulate current [13]-[15], and the other is to apply the motor's back EMF waveform functions to regulate the current [16]-[19]. In [13], the direct torque control method is adopted, but the back EMF and phase current need to be measured. So, the complexity of the circuit and software is increased.

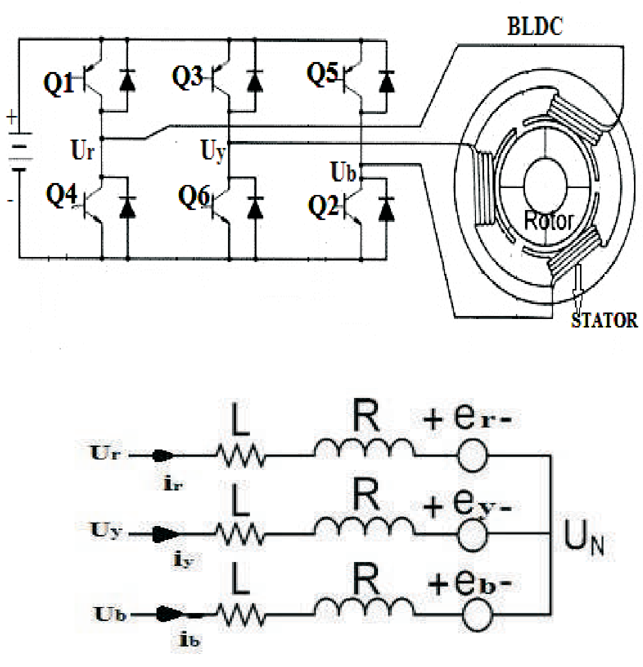


Fig. 1. Block diagram of BLDC drive system.

In [15], reduced switching frequency was obtained by a prediction control method while keeping torque within the desired hysteresis band. In [16], the influence of high harmonics on the motor's torque was analyzed. In [17], the control method in which the torque ripple can be reduced by changing the dc-link voltage is analyzed and simulated, but the corresponding topology structure was not given. Aghili *et* al. proposed an optimal commutation scheme based on Fourier decomposition with back EMF and estimating the Fourier coefficients to reduce the torque ripple and speed ripple [18], [19]. Lu *et* al. proposed at torque method for minimizing the torque ripple of BLDC motor with nonideal back EMF [20], but the diode freewheeling of the inactive phase was not considered and the modulation scheme is PWM_PWM. For space application, the magnets and the sensors of the BLDC motor are made to tight tolerances, so the manufacturing imprecision is not an issue.

This paper proposed a new current control method for the BLDC motors with nonideal back EMF. In this method, PWM_ON_PWM method is used to eliminate the current through the freewheeling diode when the phase is inactive. The motor's phase current, angular position, and speed are measured in real time and the duty cycle is precalculated in the designed current controller to control the phase current.

In addition, commutation time is calculated in the controller and speed is regulated by proportional integral (PI) controller Simulation and experimental results showed that, compared with the conventional current control method, the new control method can reduce the torque ripple effectively.

DESIGNING OF TORQUE CONTROL METHOD

The three-phase star connected BLDC motor is connected and is fed by a conventional three-phase voltage source inverter. Its configuration is shown in Fig. 1, where R, L, e, U, i, U_N, and U_d, represents the armature resistance, inductance, back EMF, terminal voltage, phase current, motor neutral voltage, dc-link voltage, respectively. r, y, b are the three phases.

The assumption made for the development of BLDC motor model are:

1) iron and stray losses are neglected
2) three-phase winding are symmetrical.

The voltage equations of three winding with phase variables are

$$U_r \quad Ri_r \quad L\frac{di_r}{dt} \quad e_r \quad U_N \qquad (1)$$

$$U_y \quad Ri_y \quad L\frac{di_y}{dt} \quad e_y \quad U_N \qquad (2)$$

$$U_b \quad Ri_b \quad L\frac{di_b}{dt} \quad e_b \quad U_N \qquad (3)$$

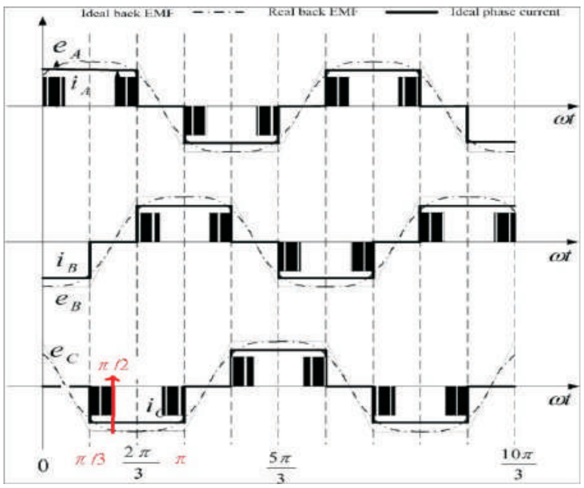
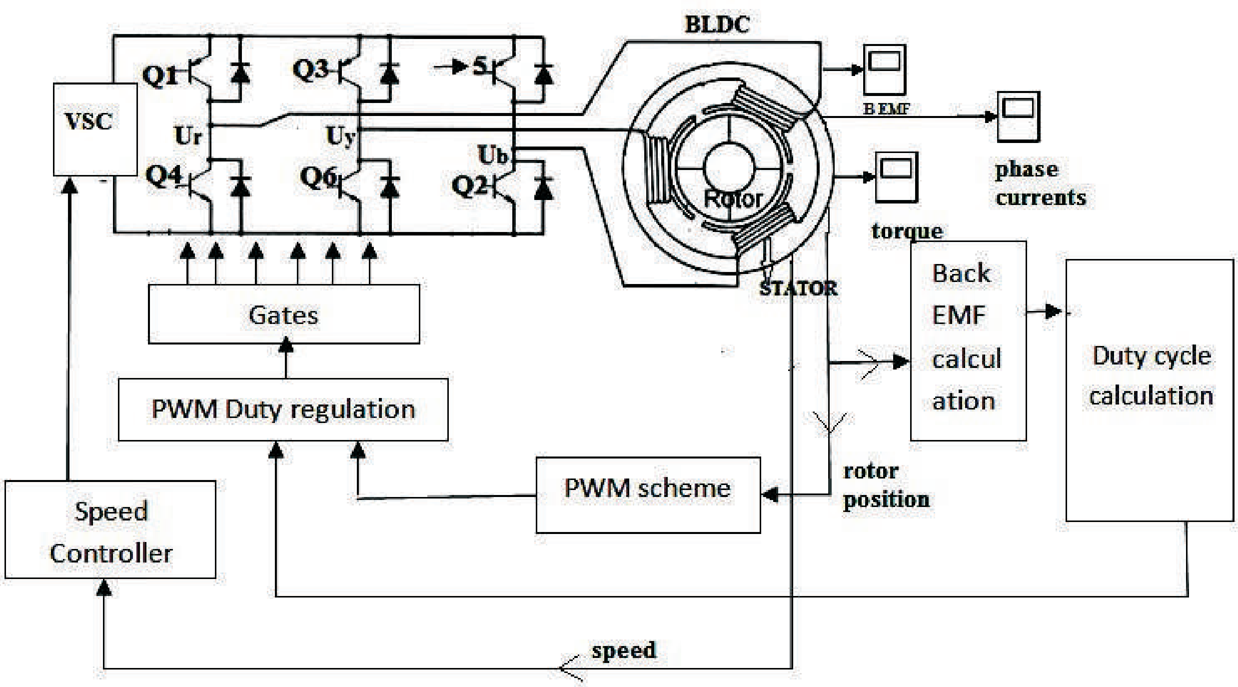


Fig. 2. PWM_ON_PWM pattern

$$Te \quad (\frac{e_r i_r \quad e_y i_y \quad e_b i_b}{Z}) \qquad (4)$$

The above is the equation of the electromagnetic torque, Where T_e is the electromagnetic torque of motor, Z is the mechanical angular velocity of rotor. As three windings are connected as star, the relationship of three-phase current

$$i_r \quad i_y \quad i_b \quad 0 \qquad (5)$$



Block diagram of a BLDC motor drive control system

A. At Commutation Period

Assuming at a particular commutation process, the current transferring from phase A to B is considered, T1 is switched OFF and T2 is switched ON, T3 is chopping, so the three-phase voltage equations are

$$U_r \quad Ri_r \quad L\frac{di_r}{dt} \quad e_r \quad U_N \quad 0 \qquad (6)$$

$$U_y \quad Ri_y \quad L\frac{di_y}{dt} \quad e_y \quad U_N \quad D u u_d \qquad (7)$$

$$U_b \quad Ri_b \quad L\frac{di_b}{dt} \quad e_b \quad U_N \quad 0 \qquad (8)$$

From the above three equations, the neutral voltage can be described as

$$U_N \quad \frac{D u u_d - e_r - e_y - e_b}{3} \qquad (9)$$

Substituting (9) into (6), (7), and (8), then differential functions of phase current are shown as

$$Ri_r \quad L\frac{di_y}{dt} \quad e_r \quad U_N \quad \frac{e_y \quad e_b \quad 2e_r \quad D u u_d}{3} \quad u_{a1} \qquad (10)$$

$$Ri_y \quad L\frac{di_y}{dt} \quad Duu_d \quad e_y \quad U_N \quad \frac{2Duu_d \quad e_r \quad e_b \quad 2e_y}{3} \quad u_{b1} \qquad (11)$$

$$Ri_b \quad L\frac{di_b}{dt} \quad e_b \quad U_N \quad \frac{e_r \quad e_y \quad 2e_b \quad D u u_d}{3} \quad u_{c1} \qquad (12)$$

With the initial condition of $i_r(t=0)=I$, $i_y(t=0)=0$, and $i_b(t=0)= -I$, (10) and (11) can be solved as

$$i_r \quad \frac{u_{a1}}{R} \quad (I \quad \frac{u_{a1}}{R})e^{(\frac{R}{L})t} \qquad (13)$$

$$i_y \quad \frac{u_{b1}}{R} \quad \frac{u_{b1}}{R} e^{(\frac{R}{L})t} \qquad (14)$$

Through Taylor series Expanding $e^{(\frac{R}{L})t}$ and neglecting its quadratic term or more. The first-degree term can be derived as $e^{(\frac{R}{L})t} \quad 1 \quad (\frac{R}{L})t$ Substituting it into (13) and (14), the time t_{a1} when i_A decreases from 1 to 0 an the time t_{b1} when i_B increases from 0 to 1 can be solved as

$$t_{a1} \quad \frac{3IL}{3IR \quad 2e_r - e_y - e_b \quad D u u_d} \qquad (15)$$

$$t_{b1} \quad \frac{3IL}{2D u u_d \quad e_r \quad e_b \; - 2e_y} \qquad (16)$$

If the motor has no commutation torque ripple on the condition working at PWM_ON_PWM scheme, t_{r1} must be equal to t_{y1}, and neglecting the influence of the resistance, the duty cycle of commutation period can be determined as

$$D(k) \quad \frac{e_r(k) \quad e_y(k) - 2e_b(k)}{u_d} \qquad (17)$$

For 0 < D(k) < 1, it can be deduced from (17) that the commutation torque ripple cannot be restrained through regulating duty cycle of PWM. In (16), overlapping commutation torque ripple. In this type of method, the switch T1 is still chopping at the time of Δt after phase-change point, and the three-phase voltage equations are

$$U_r \quad S u u_d \quad Ri_r \quad L\frac{di_r}{dt} \quad e_r \quad U_N \qquad (18)$$

$$U_y \quad u_d \quad Ri_y \quad L\frac{di_y}{dt} \quad e_y \quad U_N \qquad (19)$$

$$U_b \quad (1 - S) \quad u_d \quad Ri_b \quad L\frac{di_b}{dt} \quad e_b \quad U_N \qquad (20)$$

Where S1is the switching function and S=1 denote switching ON and S=0 denote switching OFF. In every carrier cycle of PWM, S maintains 1 during D_2T_S and the neutral voltage U_N can be solved from (18), (19), and (20) shown as follows:

$$U_N \quad \frac{2u_d \quad e_r \quad e_y \quad e_b}{3} \qquad (21)$$

Substituting (21) into (18) and (19), the effect of the resistance is neglected, and the differential functions of phase current can be described as

$$L\frac{di_r}{dt} \quad D_2 u u_d \quad e_r \quad U_N$$

$$\frac{(3D_2 \quad 2)u_d \quad e_y \quad e_b \quad 2e_r}{3} \quad u_{a2} \quad (22)$$

$$Ri_y \quad L\frac{di_y}{dt} \quad u_d \quad ey \quad U_N$$

$$\frac{u_d \quad e_r \quad e_b \quad 2e_y}{3} \quad u_{b2} \quad (23)$$

Similarly the time t_{r2} when i_r decreases form 1 to 0 an the time t_{r2} when i_B increases from 0 to 1 can be solved as (24) and (25) with the same method

$$ta2 \quad \frac{3IL}{2e_r - e_y - e_b \quad (3D_2 - 2) u u_d} \qquad (24)$$

$$tb2 \quad \frac{3IL}{u_d \quad e_r \quad e_b - 2e_y} \qquad (25)$$

Fig.3. Measured waveform of back EMF

Fig.4.Waveform of angular position, speed and back EMF

So the duty cycle of PWM can be solved as (26) when motor works at medium and high speeds

$$D_2(k) \quad 1 \quad \frac{e_r(k) \quad e_y(k) - 2e_b(k)}{3u_d} \qquad (26)$$

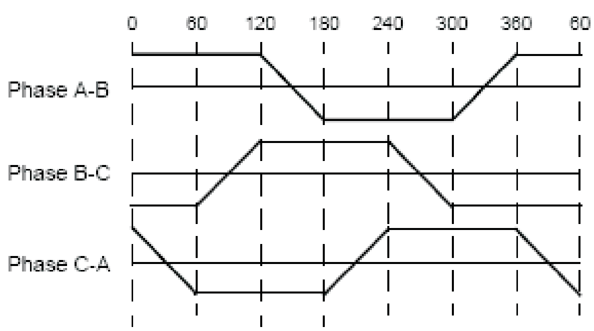


Fig. 3.Trapezoidal back EMF of BLDC motor

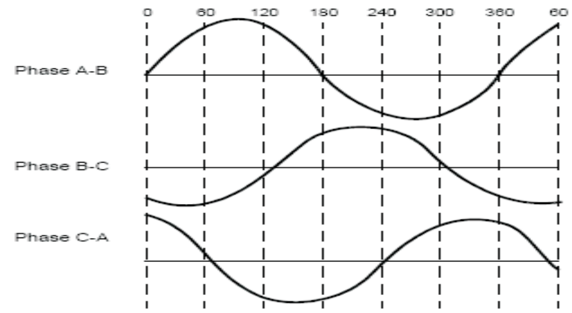


Fig.4.Sinusoidal back EMF of BLDC motor

B. ***Speed regulation by PI controller along with voltage source controller***

The PI controller is used as the regulator to track the actual motor speed and also apply the speed control input. Based on speed control input and present and past errors (proportional and integral values), the closed-loop control either increases or decreases the input voltage for the BLDC motor , which in turn controls the speed of the motor.

The difference between the expected and measured speeds gives the proportional error and this is accumulated every time to generate the integral error. With the proportional and the integral error, the PI control output is calculated as

PI Control Output =
Kp × Proportional Error + Ki × Integral Error (27)

Therefore, PI controllers (with derivative parameter Kd = 0) are used in most closed-loop processes to provide a balance of complexity and capability. Also, these controllers are simpler to tune compared to the PID controllers.

The voltage source controller supplies the DC voltage to the voltage source inverter according to the signal from PI controller.

C. Measuring Method of Back EMF

BLDC motor is proportional to the angular speed because of the back electromotive force, the waveform function can be described as

$$\begin{cases} e_r(c) = g_r(c)\,\omega_m \\ e_y(c) = g_y(c)\,\omega_m \\ e_b(c) = g_b(c)\,\omega_m \end{cases} \quad (28)$$

The angular of motor can be measured from the photoelectric encoder fixed on the motor shaft, so the back EMF of every angle can be measured through offline mode. The waveform of three phase back EMF is shown as Fig. 3. Hence, it is possible to measure the back EMF of phase r only at different speeds, and the corresponding relationship among the motor's angular position, speed, and back EMF are considered. Back EMF by the practical BLDC motor may be sinusoidal which can be taken as nonideal back emf of BLC motor.

SIMULATION RESULTS

To verify the feasibility of the new proposed current control method, simulations based on conventional current control method and the new current control method are carried out for the BLDC motor as follows.

The simulated waveforms using H_PWM_L_ON patters(High _PWM_Low_ON) are given in Figs. 5-7. The carrier wave cycle is 20K and the duty cycle is 50%.

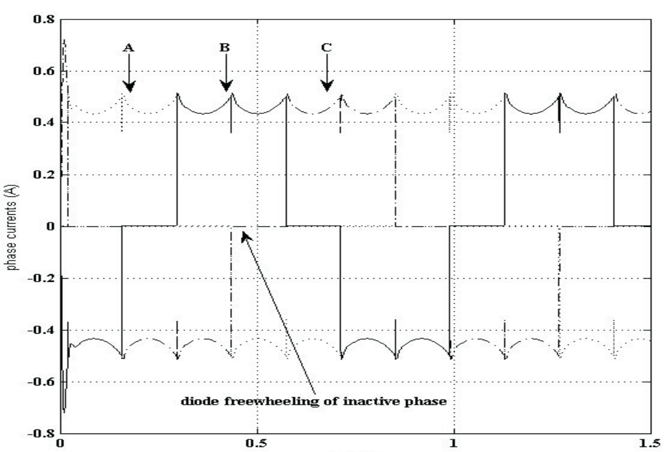


Fig.5. Simulated current using H_PWM_L_ON pattern

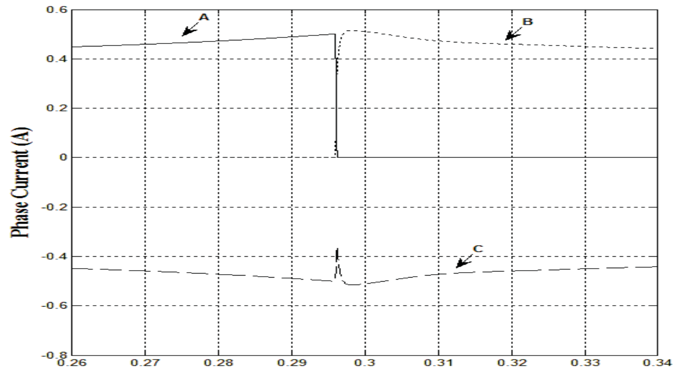


Fig.6. Phase current using H_PWM_L_ON pattern at commutation period

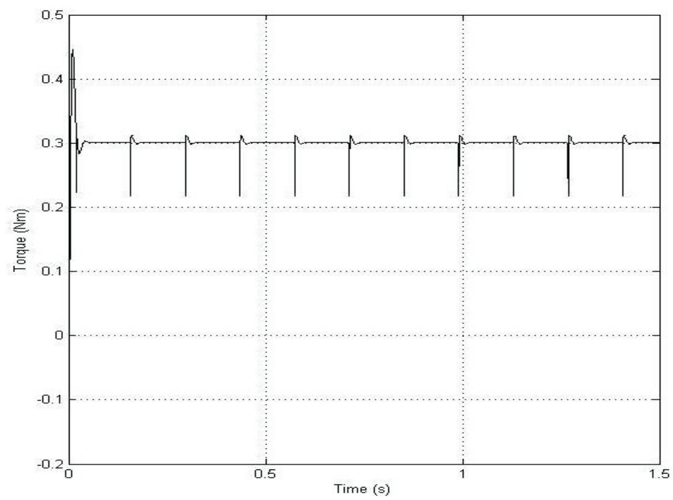


Fig.7. Simulated torque using H_PWM_L_ON pattern

Fig. 5 shows the simulated three-phase current waveform. It shows that the current ripple produced by the non ideal back EMF and changing with commutation exists and there are large current ripples at the phase-change point. Moreover, the current ripples exist on the inactive phase.

Fig. 6 shows three-phase current waveform at the commutation period. During this time, T1 is switched OFF, T3 is switched ON and chopping, and T2 is ON. It shows that the descending rate of phase current A is faster than the rising rate of phase current B, and commutation current ripple is produced on the current of phase C.

Fig. 7 shows the torque waveform using the traditional current control method. in this figure, not only large commutation torque ripple, but also periodic torque ripple produced by the nonideal back EMF change with current commutation.

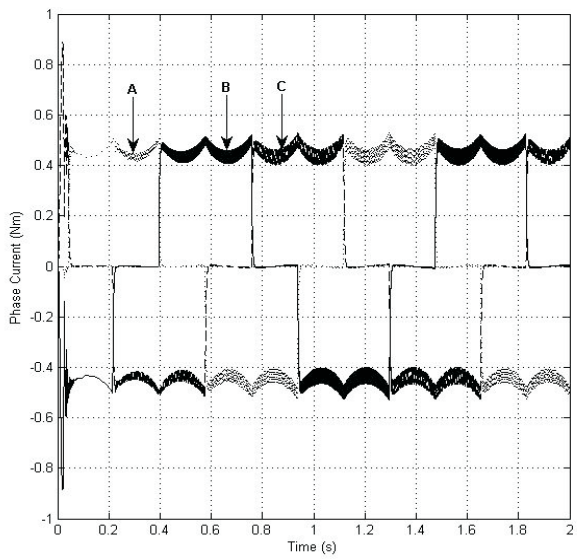


Fig.8. Simulated current using the new current control method in low speed

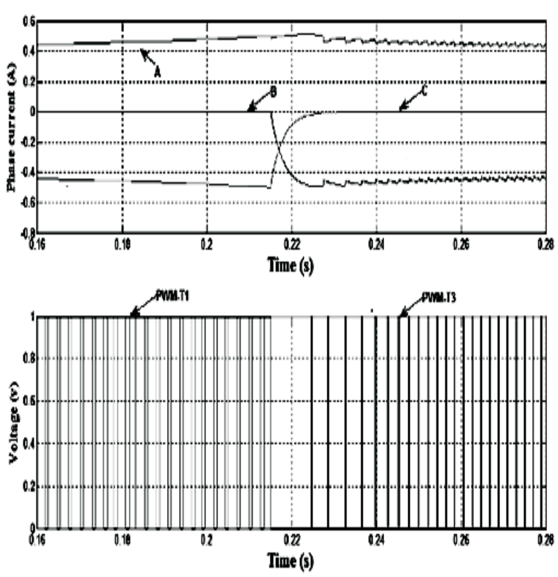


Fig.9. Simulated current and PWM waveform using the new current control method at commutation in low speed

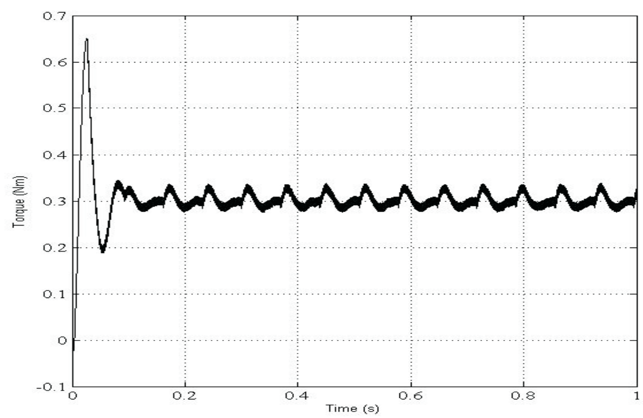


Fig.10. Simulated torque using the new current control method in low speed

The simulated waveform using a new current controller when motor works at low speed are given in Figs. 8-10. Fig. 8 shows the simulated three-phase current waveform. Comparing with Fig. 5, the commutation torque ripple and the diode freewheeling of the inactive phase are eliminated.

Fig. 9 shows the three-phase current waveform and the PWM waveform of switch T1 and T3 at the commutation period. It can be concluded that, when T1 switches OFF and T3 switches ON, the duty cycle of T3 will be increased, and also the current rising rate of phase B will speed up.

So, the current rising rate and the descending rate of phase A are almost equal. There is no ripple on the current of phase C and the commutation torque ripple is eliminated.

Fig. 10 shows the torque waveform of the motor. Comparing with Fig. 7, the torque ripple is smaller using a new current controller on the condition that the output torque is same.

Figs. 8-10 are given to show the simulated waveforms using a new current controller when motor works at low speed.

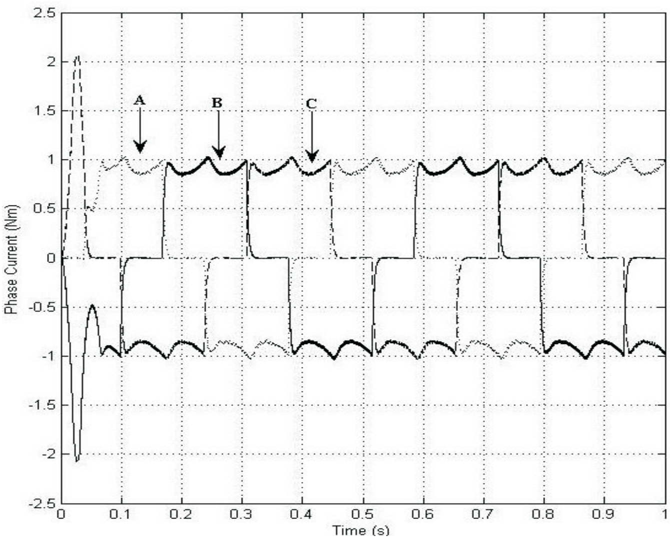


Fig.11. Simulated current using the new current control method in high speed.

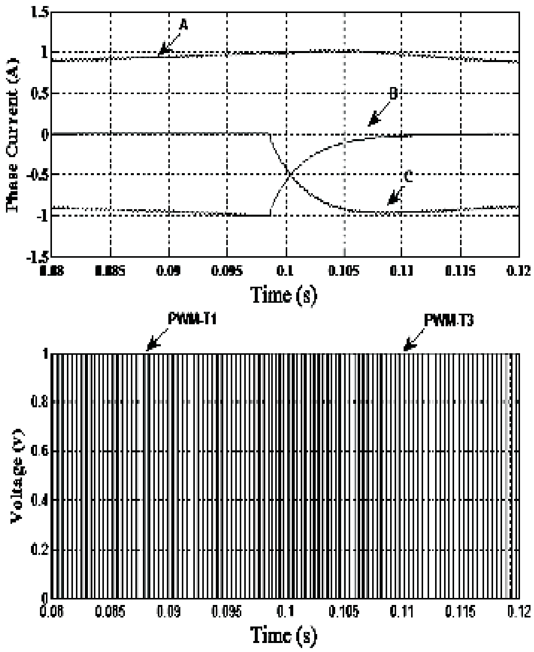


Fig.12. Simulated current and PWM waveform using the new current control method at commutation period with high speed

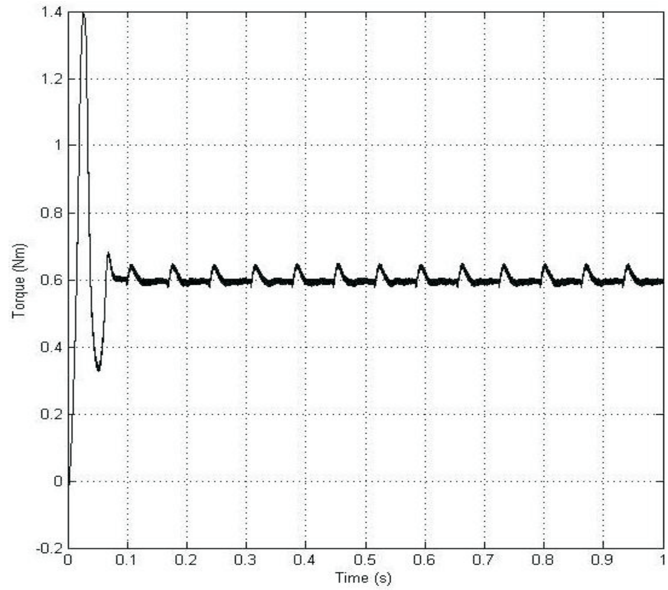


Fig.13. Simulated torque using the new current control method with high speed

In Figs. 11 and 12, it can be seen that, when the motor works at high speed and the current transfers from phase A to phase B, the switch of T1is not OFF and the switch T3 is ON at the phase-change point, and T1 is switched OFF then. With this method, the current rising rate of phase A is equal to the current descending rate of phase B's current, and the commutation torque ripple is restrained. Fig. 13 shows the conclusion. The torque ripple is 6.3% of the outputting torque at high speed using the new current control scheme.

In Figs. 14 the BLDC motor rotates at low speed with reference speed given as 100 rpm which is controlled by a PI controller

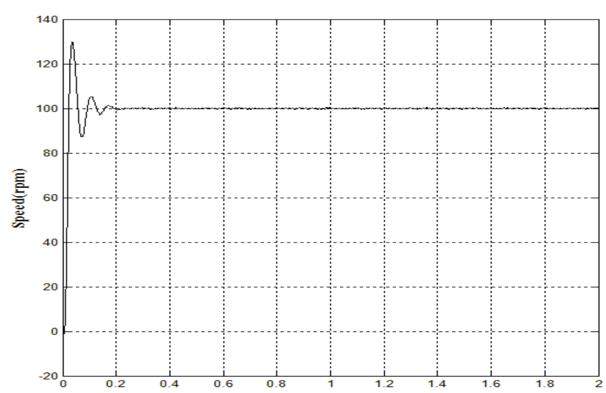


Fig.14. Simulated low speed of 100 rpm using a new control method.

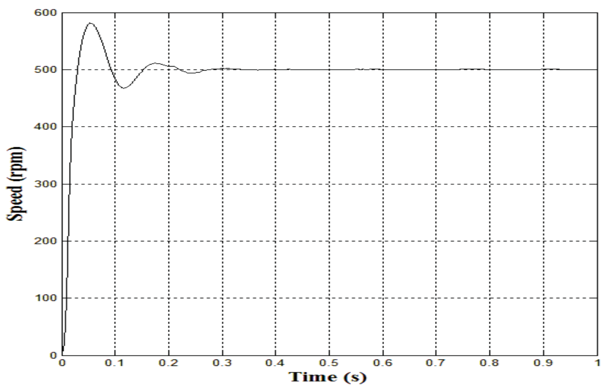


Fig.15. Simulated high speed of 500 rpm using a new control method.

In Figs. 15 the BLDC motor rotates at high speed with reference speed given as 500 rpm which is controlled by the closed loop speed control by PI controller along with voltage source controller.

CONCLUSION

Hence a new current control method is proposed with a three-phase BLDC motor with nonideal back EMF. The PWM_ON_PWM pattern is used to eliminate the diode freewheeling of inactive phase and also reduces the power dissipation. When the motor works at high speed, overlapping commutation scheme is used. When the motor works at low speed, the torque ripple is restrained by speeding up the turn-ON phase current through increasing the duty of PWM. The current controller gives the commutation times in both low and high speeds. Aiming at the nonideal back EMF, the duty is adjusted according to the speeds to eliminate torque ripple and it is calculated in the current controller by measuring the angular position, speed, and the offline measured back EMF. By using PI (Proportional Integral) controller the speed of the brushless direct current motor is regulated. The PI controller compares the reference speed given and speed calculated in real time and gives signal to voltage source inverter which either increases or decreased the input voltage to the motor according to the difference between the two speeds. The simulated results carried out on the brushless direct current motor validates the validity of the proposed current control method.

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