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Investigating the Effect of Different PWM Modes on Ripple Reduction in Five-Phase BLDC Motor with New Method

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Abstract

Torque ripple is one of the main drawbacks of brushless DC motors. In the case of three phase motors, PWM modes have a significant effect on the generated torque ripple. So, like three phase BLDC motors, we investigate the effect of different PWM modes on torque ripple of five-phase BLDC motor that has less torque ripple in high speed. In this investigation we will show that freewheeling current in inactive phase is important factor in torque ripple. Also simulation in matlab/Simulink prove this event.

Keywords*: five-phase BLDC motor, PWM control, neutral point*

1. Introduction

BLDC motors with trapezoidal induced emf waveform have significant advantages such as high efficiency, good power density, operation in high speeds and requirement to less protection. So, these motors are widely used in industries like computer, home appliances, industrial automation, etc [1]. However, the main drawback of these motors is the existence of high ripple in output torque. The major cause of the generated ripple is due to turn-on of freewheeling diodes connected to inactive phase and current flow in this phase. Two factors lead to turn-on of diodes connected to the inactive phase. First one is the inductive characteristic of motor windings which prevents from being zero of inactive phase current immediately after switch-off. So it takes time for the current to become zero and this leads to current flow in inactive phase. This procedure and its effect on torque ripple has been investigated completely in [2]. Second factor is the existence of induced emf and switching method which, in certain conditions cause the forward bias of diodes connected to inactive phase and lead to current flow in inactive phase and makes torque ripple [3]. The second factor has wider range and effect. As mentioned in the abstract, phase increasing is one of the ripple reduction methods in high speeds [4, 5]. Also, switching method is effective in torque ripple of motors with increased phase. In this paper, we intend to investigate the different PWM modes of five-phase motor and its effect on torque ripple as it has been already done for three phase motors in [6-8].

This paper is organized as follows. Five phase BLDC motor will be introduced in section II. In section III, different PWM modes will be analyzed. The simulation of Torque in different PWM modes and conclusion are presented in section IV and V, respectively.

2. Introduction of Five Phase BLDC Motor

A five phase motor along with its drive are shown in Figure 1.

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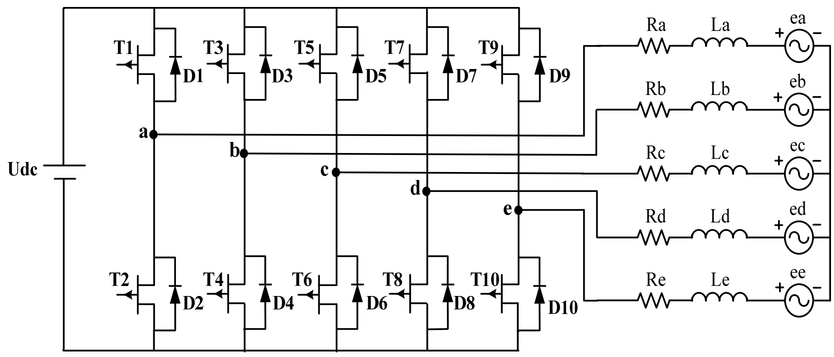

Figure 1. Equivalent Circuit of Five-phase BLDC Motor

Permanent magnet is placed on the rotor and the waveform of the induced emf will be trapezoidal. This motor is supplied by a rectangular current, so the output torque is theoretically constant and without ripple. But actually it is not true and there will be ripple in the output torque due to the conduction of freewheeling diodes and current flow in inactive phase [3]. In normal operation, four phases of the five phase motor are active and one is inactive. Two of four active phases have positive current flow and two other phases have negative current flow. Figure 2 shows the induced emf waveform and the phase current of five phase BLDC motor**.**

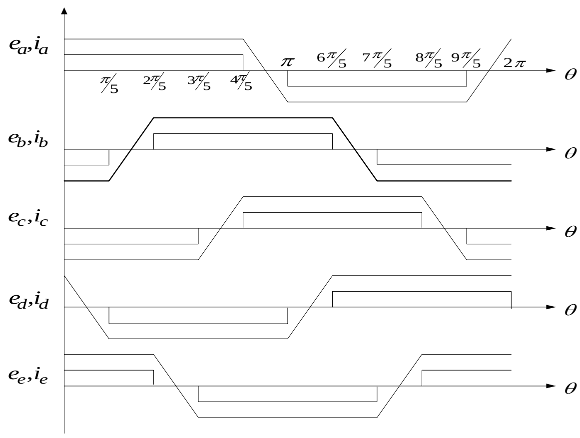

Figure 2. The Waveform of Induced emf and the Phase Current of Five Phase BLDC Motor

3. Analysis of Different PWM Modes

There are four PWM modes in three phase motors: ON_PWM, PWM_ON, H_ON_L_PWM and H_PWM_L_ON [6, 7]. In this section, we investigate the effect of these four modes on torque ripple of five phase motor.

3.1. ON_PWM Mode

The induced emf waveform and the switching scheme of five phase BLDC motor drive are shown in Figure 3. We assume that the motor operates in A&B region. The equations of motor terminal voltages are expressed as (1) where U_{dc} is the dc link voltage and S is the switching function of each phase. When S=1, the upper switch is on and the lower switch is off, and when S=0, the lower switch is on and the upper switch is off.

$$\begin{bmatrix} S_b U_{dc} \\ U_{dc} \\ S_d U_{dc} \\ 0 \end{bmatrix} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & L & 0 \\ 0 & 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} e_b \\ e_c \\ e_d \\ e_e \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \\ V_n \end{bmatrix} \quad \Rightarrow V_n = \frac{1}{4}(1 + S_b + S_d) \tag{1}$$

In Equation (1), i_b, i_c, i_d, i_e are the phase currents, e_a, e_b, e_c, e_d, e_e are the induced phase voltages, V_n is neutral voltage with reference to ground, R is the winding resistance of each phase and L is the inductance of phase. Also $i_b=i_c=-i_d=-i_e$ and $e_b=e_c=-e_d=-e_e$. According to the different values of S_b , S_d, the neutral voltage will have different values as in (2).

$$Vn = \begin{cases} \frac{1}{4}U_{dc} & S_b = S_d = 0 \\ \frac{1}{2}U_{dc} & S_b = 0, Sd = 1 \\ & S_b = 1, S_d = 0 \\ \frac{3}{4}U_{dc} & S_b = S_d = 1 \end{cases} \tag{2}$$

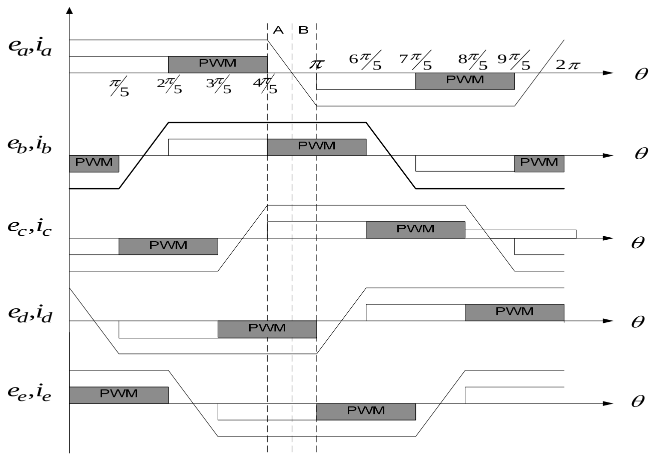

Figure 3. The Induced Voltage Waveform and Switching Scheme of Five Phase BLDC Motor Drive in ON-PWM Mode

The induced voltage is positive in region A. It can be proved that the induced voltage in five phase motor is always less than $0.5U_{dc}$ [3]. From Equation (2), the terminal voltage of inactive phase a is expressed as:

$$0 < e_a < \frac{1}{2}U_{dc} \quad \Rightarrow V_n < U_a = e_a + V_n < \frac{1}{2}U_{dc} + V_n$$
$$\Rightarrow \begin{cases} \frac{1}{4}U_{dc} < U_a < \frac{3}{4}U_{dc} \\ \frac{1}{2}U_{dc} < U_a < U_{dc} \\ \frac{3}{4}U_{dc} < U_a < \frac{5}{4}U_{dc} \end{cases} \quad \Rightarrow \frac{1}{4}U_{dc} < U_a < \frac{5}{4}U_{dc} \tag{3}$$

According to (3), since the terminal voltage exceeds U_{dc}, then diode D_1 is forward biased and causes current flow in inactive phase a. Now we assume to be in operating region B. Then the terminal voltage of phase a is expressed as:

$$-\frac{1}{2}U_{dc}<e_a<0 \quad \Rightarrow V_n-\frac{1}{2}U_{dc}<U_a=e_a+V_n<V_n$$
$$\Rightarrow\begin{cases}-\frac{1}{4}U_{dc}<U_a<\frac{1}{4}U_{dc}\\ 0<U_a<\frac{1}{2}U_{dc}\\ \frac{1}{4}U_{dc}<U_a<\frac{3}{4}U_{dc}\end{cases} \quad \Rightarrow -\frac{1}{4}U_{dc}<U_a<\frac{3}{4}U_{dc} \tag{4}$$

From Equation (4), since the terminal voltage becomes negative then diode D_2 is forward biased and causes current flow in inactive phase a. Therefore in ON_PWM mode, current flows in both region A&B.

3.2. PWM_ON Mode

The induced emf waveform and the switching scheme of the motor drive are shown in Figure 4. With a deduction similar to (1), the neutral voltage is as:

$$V_n=\frac{1}{4}(1+S_c+S_e) \tag{5}$$

According to the different values of S_c and S_e, the neutral voltage will have different values as:

$$Vn=\begin{cases}\frac{1}{4}U_{dc} & S_c=S_e=0\\ \frac{1}{2}U_{dc} & S_c=0, S_e=1\\ & S_c=1, S_e=0\\ \frac{3}{4}U_{dc} & S_c=S_e=1\end{cases} \tag{6}$$

With a procedure similar to what we used for (3) and (4), it is concluded that when the motor is in the operating region A, the current of inactive phase a is in the negative direction and when it is in the operating region B, the current of inactive phase a flows in the positive direction. So the current flows in both regions A and B in PWM_ON mode and causes torque ripple.

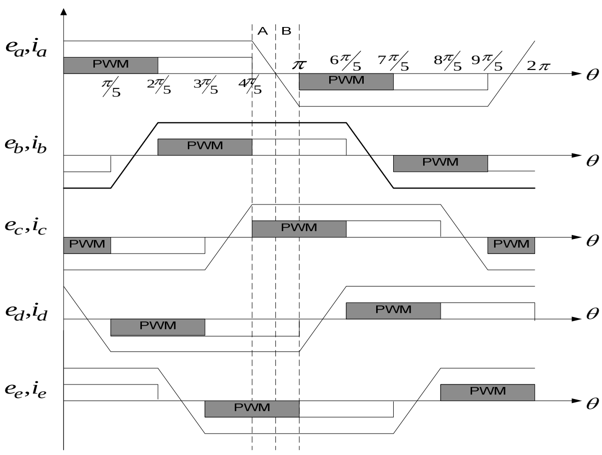

Figure 4. The Induced Voltage Waveform and Switching Scheme of the Five Phase BLDC Motor Drive in PWM_ON Mode

3.3- H_ON_L_PWM mode

The induced voltage waveform and switching scheme of five phase BLDC motor drive are shown in Figure 5. The equations of motor terminal voltages in region A,B are expressed as:

$$\begin{bmatrix} U_{dc} \\ U_{dc} \\ S_d U_{dc} \\ S_e U_{dc} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & L & 0 \\ 0 & 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} e_b \\ e_c \\ e_d \\ e_e \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \\ V_n \end{bmatrix} \quad \Rightarrow V_n = \frac{1}{4}(2 + S_d + S_e) \tag{7}$$

According to the different values of S_d , S_e, the neutral voltage will have different values as in (8). It is assumed that the motor is in operating region A.

$$Vn = \begin{cases} \frac{1}{2} U_{dc} & S_d = S_e = 0 \\ \frac{3}{4} U_{dc} & S_d = 0, S_e = 1 \\ & S_d = 1, S_e = 0 \\ U_{dc} & S_d = S_e = 1 \end{cases} \tag{8}$$

The induced voltage is positive in this region. With a procedure similar to that previously mentioned, the voltage terminal of the inactive phase a is as (9).

$$0 < e_a < \frac{1}{2} U_{dc} \quad \Rightarrow V_n < U_a = e_a + V_n < \frac{1}{2} U_{dc} + V_n$$
$$\Rightarrow \begin{cases} \frac{1}{2} U_{dc} < U_a < U_{dc} \\ \frac{3}{4} U_{dc} < U_a < \frac{5}{4} U_{dc} \\ U_{dc} < U_a < \frac{3}{2} U_{dc} \end{cases} \quad \Rightarrow \frac{1}{2} U_{dc} < U_a < \frac{3}{2} U_{dc} \tag{9}$$

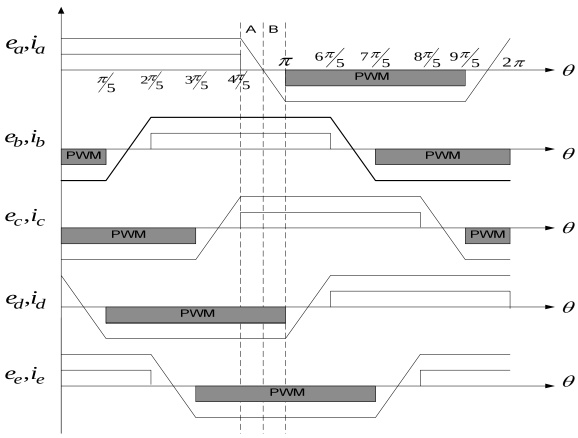

Figure 5. The Induced Voltage Waveform and Switching Scheme of Five Phase BLDC Motor in H_ON_L_PWM Mode

Since the terminal voltage of phase a exceeds U_{dc} then diode D_1 is forward biased and causes current flow. Now it is assumed that the motor operates in region B. With a deduction similar to (9), Equation (10) is obtained. From (10) we conclude that the diode is not forward biased in region B and current does not flow in inactive phase a. So the current only flows in region A in H_ON_L_PWM mode, i.e. the torque ripple is lower.

$$-\frac{1}{2}U_{dc} < e_a < 0 \quad \Rightarrow V_n - \frac{1}{2}U_{dc} < U_a = e_a + V_n < V_n$$
$$\Rightarrow \begin{cases} 0 < U_a < \frac{1}{2}U_{dc} \\ \frac{1}{4}U_{dc} < U_a < \frac{3}{4}U_{dc} \\ \frac{1}{2}U_{dc} < U_a < U_{dc} \end{cases} \quad \Rightarrow 0 < U_a < U_{dc} \tag{10}$$

3.4. H_PWM_L_ON Mode

The induced voltage waveform and switching scheme of five phase drive are shown in Figure 6. The terminal voltages of active phases in region A, B are expressed as:

$$\begin{bmatrix} S_b U_{dc} \\ S_c U_{dc} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & L & 0 \\ 0 & 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} + \begin{bmatrix} e_b \\ e_c \\ e_d \\ e_e \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \\ V_n \end{bmatrix} \quad \Rightarrow V_n = \frac{1}{4}(S_b + S_c) \tag{11}$$

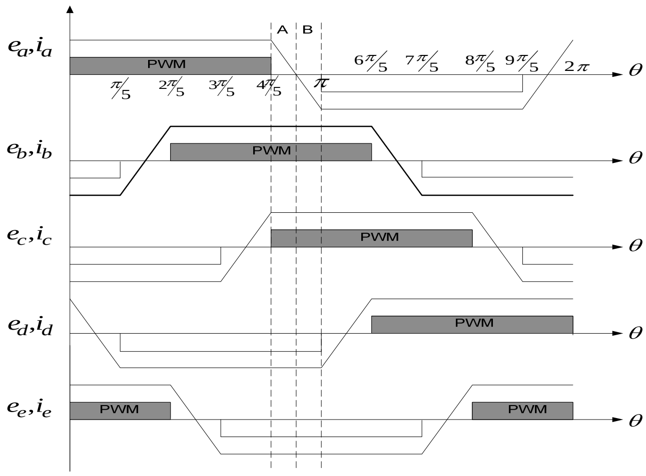

Figure 6. The Induced Voltage Waveform and Switching Scheme of Five Phase BLDC Motor in H_PWM_L_ON Mode

According to the different values of S_b , S_c, the neutral voltage is obtained as follows:

$$Vn = \begin{cases} 0 & S_b = S_c = 0 \\ \frac{1}{4}U_{dc} & S_b = 0, S_c = 1 \\ & S_b = 1, S_c = 0 \\ \frac{1}{2}U_{dc} & S_b = S_c = 1 \end{cases} \tag{12}$$

It is assumed that the motor is in operating region A. The terminal voltage of phase a is obtained with a similar deduction:

$$0 < e_a < \frac{1}{2}U_{dc} \qquad \Rightarrow 0 < U_a < U_{dc} \qquad (13)$$

According to (13) it is concluded that the current does not flow in region A. In region B, a similar deduction leads to Equation (14)

$$-\frac{1}{2}U_{dc} < e_a < 0 \qquad \Rightarrow -\frac{1}{2}U_{dc} < U_a < \frac{1}{2}U_{dc} \qquad (14)$$

So from (14) it is seen that the current flows in inactive phase a in operating region B. So the current only flows in region B in H_PWM_L_ON mode, i.e. the torque ripple is lower.

According to analysis presented in section 3, Table 1 shows the obtained results. Simulations in section 4 prove Table 1 results.

Table 1. Obtained Results from Section 3

	Existence of freewheeling current	Torque ripple
ON_PWM	Both A&B regions	high
PWM_ON	Both A&B regions	high
H_ON_L_PWM	Region A only	lower
H_PWM_L_ON	Region B only	lower

4. Simulation

From the analyses presented in section 3 we conclude that in H_ON_L_PWM and H_PWM_L_ON modes, the current in inactive phase 'a' only flows in one of the two regions A, B, i.e. the cause of generating torque ripple emerges less, so the torque ripple will be low. This scenario is simulated in matlab/Simulink for a motor with characteristics presented in Table. 2. Simulation method has been adapted from [3]. In this paper simulations for three-phase motor is done and we have developed the model for five phase motor. Also general description of the five-phase motor is done in [5].

Table 2. Parameters of the Five Phase Motor

R	**L**	**speed**
0.33(ohm)	0.67(mH)	800(rpm)
K_e	**K_t**	**J**
0.066(V/rpm)	1.25(N.m/A)	.0005(Kg.m^2)
T_{load}	**V_{dc}**	**Z_p**
28(N.m)	180(V)	8

Figure 7 to Figure 10 show the torque waveforms for four different control modes.

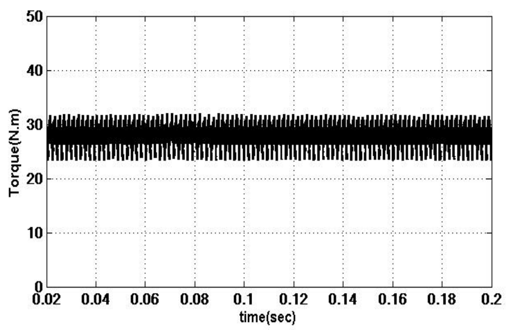

Figure 7. The Torque of H_ON_L_PWM Mode

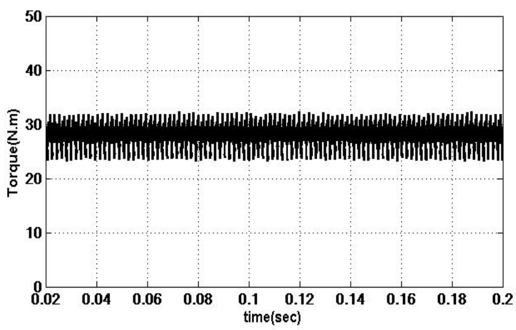

Figure 8. The Torque of H_PWM_L_ON Mode

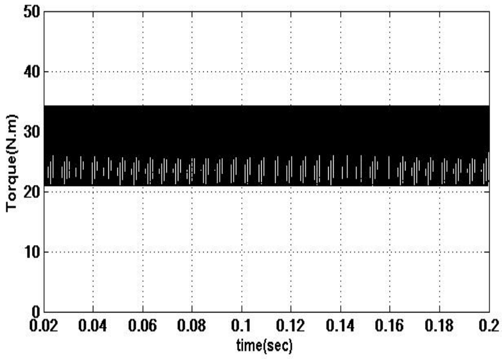

Figure 9. The Torque of PWM_ON Mode

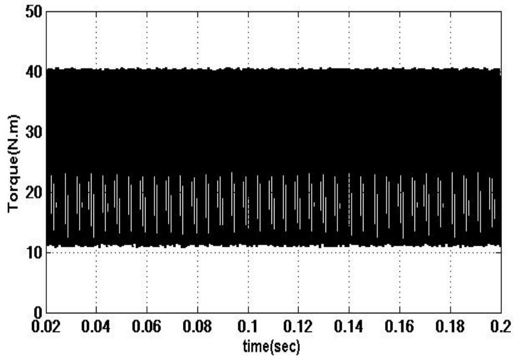

Figure 10. The Torque of ON_PWM Mode

According to Table 1, it is seen in the Figure 7-10 that torque ripple in cases 3.3 and 3.4 is less than cases 3.1 and 3.2. because in cases 3.3 and 3.4 freewheeling current flows in one region while in cases 3.1 and 3.2 freewheeling current flows in two regions A and B.

5. Conclusion

In this paper, four different control modes for five phase BLDC motor was presented as it was already done for three phase BLDC motors. The most important factor in making torque ripple was current flow in inactive phase. The analysis of this issue showed that in modes in which the control of upper and lower switches is done separately, have lower torque ripple. Simulaions in matlab/Simulink proved this result.

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