

# One-Cycle Average Torque Control of Brushless DC Machine Drive Systems

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**ABSTRACT:** This paper investigates the mitigation of torque ripple caused by non-ideal trapezoidal back electromotive force (EMF) using one-cycle average torque control algorithm. The average torque in one switching cycle is controlled to reduce the torque ripple. The feedback average torque is observed by the input energy in each switching cycle, and the energy can be calculated by measuring the DC bus voltage and current. No sophisticated observer is needed since neither the back EMF nor accurate rotor position information is required. No current sensor is required to measure the phase currents. Only two sensors are used to measure the DC bus voltage and current to compute the average torque.

**KEYWORDS:** Torque ripple; Brushless DC machine average torque; One-cycle; Non-ideal trapezoidal back EMF.

## I. INTRODUCTION

Brushless DC motors are extensively used for various industrial applications due to the advantages of simple control, robustness and high power density. Large torque ripple is the major shortcoming of BLDC that limits its application in high precision servo systems and noise-sensitive applications.

Extensive research has been carried out on the torque ripple reduction for BLDC machines with ideal trapezoidal back EMF. Generally, the phase currents of a BLDC machine are controlled to follow rectangular waveforms which are considered to be ideal for the two-phase conducting mode of the BLDC machine. During commutation, the torque generation is mainly contributed by current in the non-commutated phase. The unequal rising or falling rate of the incoming and outgoing phase currents results in a dip in the non-commutated phase current, which in turn, distorts the electromagnetic torque generation. BLDC machine rarely has the ideal trapezoidal back EMF due to many factors such as the stator winding function, magnetization direction of rotor permanent magnets and imperfections in machine manufacturing. If the phase currents are still controlled to follow rectangular waveforms for a BLDC machine with non-ideal trapezoidal back EMF, the torque will not be constant anymore and it will contain various harmonic components. The torque ripple can cause the mechanical vibration, acoustic noise and bearing damage, hence, reduce the life of the machine. In [1] current slopes during commutation interval is controlled by a proper duty ratio control by measuring the dc-link current. A dead beat current controller is used to enhance the current control performance. This method prolongs the commutation and is a complex topology. Commutation torque ripple can be minimized by PWM\_ON\_PWM switching [2]. PWM mode is used in the first 30 degrees and last 30 degrees while keeping turn-on mode in the middle 60 degrees. The dc-link voltage can be controlled to keep the incoming and outgoing phase currents changing at the same rate during commutation [3]. To get the desired dc-link voltage a SEPIC circuit is used to control the inverter input. In [4] commutation torque ripple of the brushless dc machine is eliminated with minimum commutation time by speeding up the slow one between incoming and outgoing phase currents.

Popular methods of reducing the torque ripple caused by non-ideal trapezoidal back EMF can be divided into two major categories: 1) the optimal current injection method, and 2) the direct torque control method. For the optimal current injection method, a current command including harmonics is generated to ensure the product of the phase current and the phase back EMF is constant [5]. The actual current may not follow the current command as desired due to the limited power converter switching frequency, current controller bandwidth, and microprocessor computing

power. As a result, the torque ripple cannot be reduced effectively. The second type is to use the direct torque control method, where the instantaneous torque is selected as the control variable [6]. Estimation of the instantaneous torque is investigated intensively. Information of the accurate rotor position and back EMF is required in these methods to reduce the torque ripple of BLDC machines with non-ideal trapezoidal back EMF.

In this paper the one-cycle average torque control method is used to mitigate the torque ripple of a BLDC machine with non-ideal trapezoidal back EMF. It advances and applies the one-cycle control to electric machine drive systems to control the average torque in one switching cycle to reduce the torque ripple. The feedback average torque is observed by the input energy in each switching cycle, and the energy can be calculated by measuring the DC bus voltage and current. Compared with other methods in mitigating the torque ripple of BLDC machines discussed above, the proposed method requires no information of the back EMF and the rotor position. No current sensor is needed to measure the phase current. Only two sensors are used to measure the DC bus voltage and current to compute the average torque.

## II. PRINCIPLE OF ONE-CYCLE AVERAGE TORQUE CONTROL ALGORITHM

One cycle control is a kind of nonlinear control technique [7]. The average value of the switched variable can follow its control reference within a switching cycle. This concept is known as one cycle control. It has been applied in power amplifier, power factor correction, DC-DC conversion, active power filter. This section first reviews the PWM operation algorithm for the BLDC machine drive systems. Then the principle of the one-cycle average torque control algorithm is presented.

### A. Review of PWM\_ON Drive Pattern of BLDC Machine

Figs. 1 and 2 show the typical topology of the BLDC machine drive systems and the switching functions. Each switch is operating in the PWM mode for the first 60 degrees and completely turned on for the next 60 degrees. At any time, only two phases are conducting simultaneously.

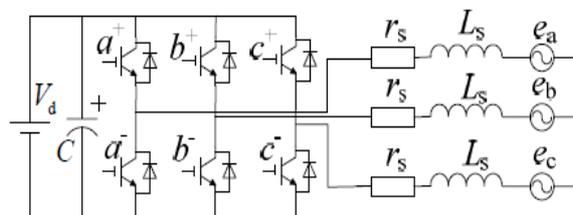


Fig. 1. Equivalent circuit of BLDC machine drive system

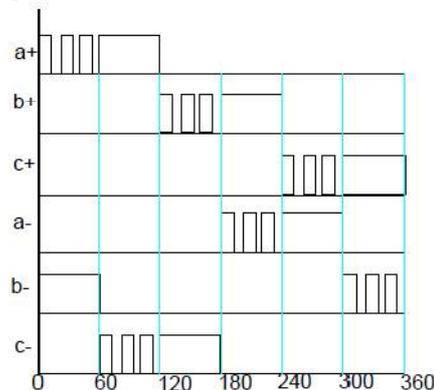


Fig. 2. PWM\_ON control pattern

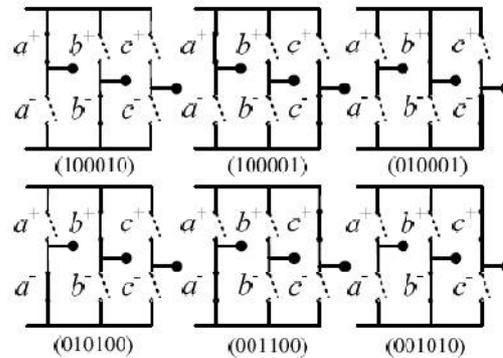


Fig. 3. Six states of inverter in BLDC machine drive

If “1” and “0” are used to represent the on and off statuses of each switch, the power converter operation modes can be described by six active statuses as shown in Fig.3: (100010), (100001), (010001), (010100), (001100) and (001010). Each vector shows the on-off statuses of a+, b+, c+, a-, b- and c-. At any instant two switches are turned on, that is upper leg switch and lower leg switch of two different phases. In the three-phase stationary reference frame, six space voltage vectors  $V_1$  to  $V_6$  can be used to represent the six active statuses as shown in Fig.4. The directions of the voltage vectors in Fig.4 are defined by the switching pattern in Fig.2. Corresponding to the active vectors, the six zero vectors can be written as to  $V_0^1$  to  $V_0^6$ . Table I shows the six zero voltage vectors of brushless DC motor drive. Zero voltage vectors are corresponding to the turn-on of only one switch.

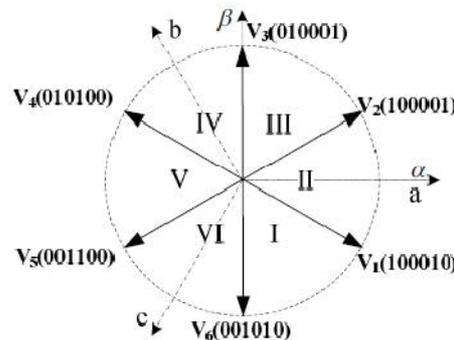


Fig. 4. Space vectors in BLDC machine drive

TABLE I. ZERO VOLTAGE VECTORS OF BLDCM DRIVE

$V_0^n$	Switching sequence
$V_0^1$	100000
$V_0^2$	000001
$V_0^3$	010000
$V_0^4$	000100
$V_0^5$	001000
$V_0^6$	000010

#### B. Principle of One-Cycle Average Torque Control

According to the principle of electromechanical energy conversion, the energy flowing into the system in one switching cycle  $dW_e$  is equal to the summation of energy change in the air-gap  $dW_m$ , the mechanical output energy  $dW_{mech}$ , and the system losses  $dW_{loss}$ :

$$dW_e = dW_m + dW_{mech} + dW_{loss} \quad (1)$$

When the electric machine operates in the steady state, the energy stored in the magnetic field reaches a dynamic balance. Thus in each switching cycle, the energy change in the air-gap is zero. Considering the switching cycle is very short, it is reasonable to assume the efficiency of the system remains constant in one switching cycle. Therefore, (1) can be written as:

$$dW_e = dW_m + dW_{mech} = \frac{1}{\eta} dW_{mech} \quad (2)$$

where  $\eta$  is the efficiency of the system. The relationship between the input energy and the average torque  $T_{av}$  in one switching cycle can be expressed as:

$$dW_e = \frac{1}{\eta} dW_{mech} = \frac{\Delta\theta}{\eta} T_{av} = k T_{av} \quad (3)$$

where  $\Delta\theta$  is the mechanical angular position change in one switching cycle and  $k$  the coefficient defined as  $\Delta\theta/\eta$  which is constant under the steady state. Based on (3), the electric machine torque variation will reflect as the DC input energy fluctuation. Therefore, the average torque  $T_{av}$  may be computed by using the energy flowing into the system for each control cycle. The effect of the coefficient  $k$  can be counted in the PI control gains. Fig.6 shows the control block diagram using the proposed one-cycle average torque control method to mitigate the torque ripple.

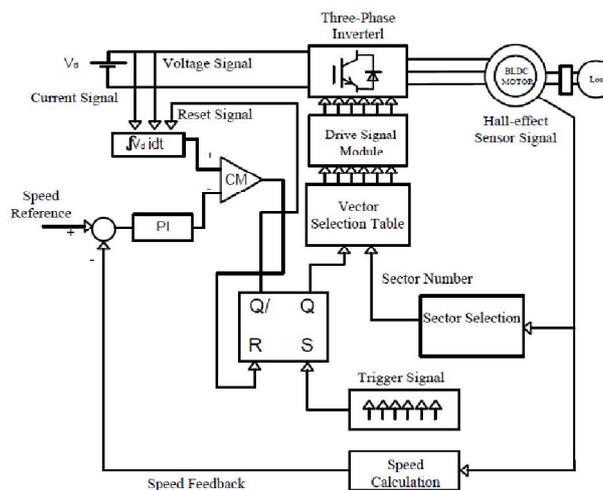


Fig. 6. Control block diagram of torque ripple mitigation using one-cycle average torque control

The output of the speed PI controller is generally taken as the electromagnetic torque command in the traditional motor control. Here, the speed control gains are designed so that the output of the controller is the energy command in each control cycle. As mentioned earlier, the DC bus voltage and current are monitored by sensors. The input energy in one control cycle is calculated by integrating the product of the DC bus voltage and current. Fig.7 shows the control block diagram of one-cycle average torque control algorithm. Fig.8 and Fig.9 demonstrate the operating principle and the flow chart respectively of the one-cycle average torque control algorithm.

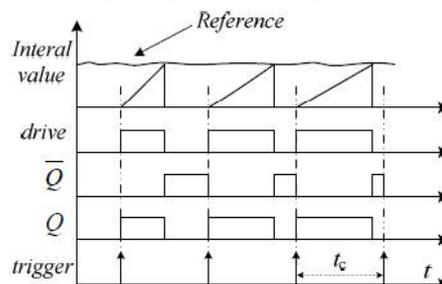


Fig. 7. Operating principle of one-cycle average torque control

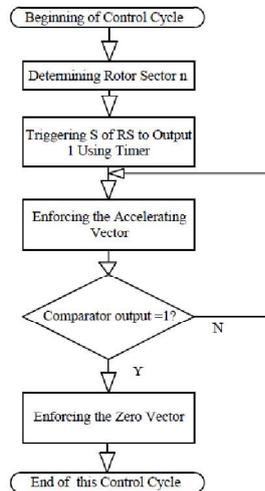


Fig. 8. Flow chart of one-cycle average torque control

At the beginning of each control cycle, a trigger signal is used to activate the integration of the DC input energy. Before the integration value reaches the reference energy, Q of the RS flip-flop is set to be 1 which means the active voltage vector will be applied. When the integration value reaches the reference energy, the energy of the system already meets the command and no extra energy is needed in this switching cycle. Therefore, Q of the RS flip-flop will be set to be 0 which means the zero voltage vector will be applied. Meanwhile, Q is set to 1 to reset the integration value. The rotor position will determine which specific active or zero voltage vector will be applied to the electric machine. Table III lists the voltage vector selection for the counter clockwise operation according to the sector definition in Fig.5.

TABLE III. VOLTAGE VECTOR SELECTION TABLE

	Rotor Position Sector "n"					
Q	I	II	III	IV	V	VI
1	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>
0	V <sub>0</sub> <sup>2</sup>	V <sub>0</sub> <sup>3</sup>	V <sub>0</sub> <sup>4</sup>	V <sub>0</sub> <sup>5</sup>	V <sub>0</sub> <sup>6</sup>	V <sub>0</sub> <sup>1</sup>

As discussed before, the torque ripple will reflect as the fluctuation in the input power or energy. The one-cycle average torque control algorithm suppresses the torque ripple by maintaining the actual input energy in each control cycle constant.

### III. SIMULATION RESULTS

In this section the influence of back EMF on the torque ripple is analyzed based on the measured back EMF waveforms of the BLDC machine. Secondly, simulation using the one-cycle average torque control is presented. The torque ripple waveform with ON\_PWM switching and PWM\_ON switching are compared.

#### A. Analysis of Torque Ripple Caused by Non-Ideal Back EMF

Fig.9. shows the ideal and actual measured three-phase back EMF. The electromagnetic torque may be written as:

$$T_e = \frac{1}{\omega_m} (e_a i_a + e_b i_b + e_c i_c) \quad (11)$$

where  $\omega_m$  is the mechanical angular velocity,  $e_a, e_b, e_c$  the three phase back EMFs and  $i_a, i_b, i_c$  the three phase currents.

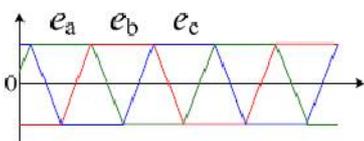


Fig. 9. Ideal trapezoidal back-EMF

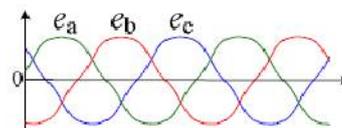


Fig. 10. Actual measured back-EMF

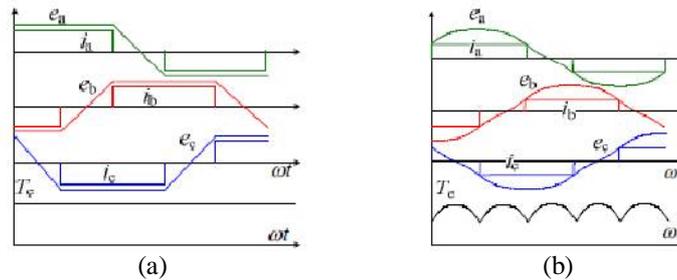


Fig. 11. Currents and back EMF of BLDC machine with (a) ideal back-EMF (b) actual back-EMF

According to (11), with ideal rectangular current, the electromagnetic torque is constant if the machine has an ideal trapezoidal back-EMF, as shown in Fig.11 (a). However, for the machine with non-ideal trapezoidal back-EMF, such as the waveforms shown in Fig.10, the electromagnetic torque is not constant when the phase-current is still the rectangular waveform. Fig.11.(b) shows the torque waveform and the frequency of the torque ripple is six times the fundamental component of the back-EMF.

#### B. Simulation and Analysis

Simulation of the One-cycle average torque control is conducted. A few parameters of the BLDC machine drive systems used in the simulation are listed in Table IV.

TABLE IV. PARAMETERS OF BLDC MACHINE DRIVE SYSTEM

DC bus voltage	48V
Armature resistance	0.02
Armature inductance	0.1mH
Number of pole-pairs	4
Rated speed	1800 rpm
Rated torque	1.5Nm
Back EMF coefficient	0.127V.s/ rad
Moment of inertia of rotor	0.001kg.m <sup>2</sup>

The input dc-link current and voltage are sensed and their product is given as an input to the integrator. The other input to the integrator is the reset input to reset the integration. Integration of the product of input current and voltage is the input energy. The input energy is compared with the reference energy. Integration starts with a trigger signal to the RS flip-flop. The trigger signals are pulses with a constant frequency of 20 kHz. Once the RS flip-flop is triggered, the corresponding power switch is turned on to implement the active voltage vector. The DC bus current and phase-current begin to increase. Part of the energy is converted into mechanical motion in the accelerating period and the other part is stored in the air-gap. If input energy is less than the reference energy then an active voltage vector corresponding to the rotor position is applied to increase the input energy. When the input energy reaches the reference, the power switch is turned off and the DC bus current falls to zero as shown in Fig.12. For the rest of this cycle, the zero voltage vector is applied and the energy stored in air-gap is converted into mechanical motion.

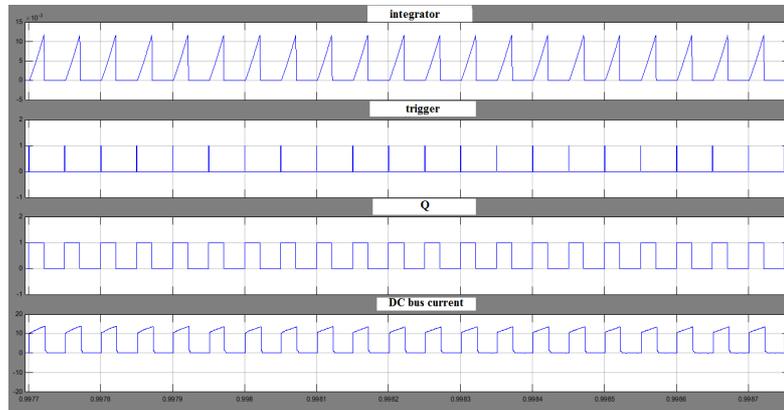


Fig. 12. Operating principle of one-cycle average torque control

Fig.13 shows the current waveforms of the phases A and B. The peak current is 13.79A and the average current is about 8.7A. The current is not perfectly rectangular. Fig.14(a) shows the electromagnetic torque waveform of the one-cycle average torque controlled brushless DC motor drive with ON\_PWM switching. The torque waveform is flat without the arc-shaped ripples. The average torque is 1.5Nm. The torque ripple is mitigated and its magnitude is about 0.4Nm. Fig.14(b) shows the electromagnetic torque waveform of the one-cycle average torque controlled brushless DC motor drive with PWM\_ON switching. Here commutation torque ripple is less as compared with the ON\_PWM switching. From Fig.14(a) and Fig.14(b) we can see that there are some spikes in the torque waveform in the commutation interval. These are called commutation torque ripples. Here the commutation torque ripple is not considered.

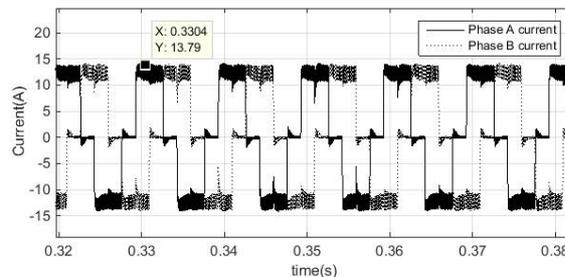


Fig. 13. Phase currents in one-cycle average torque control.

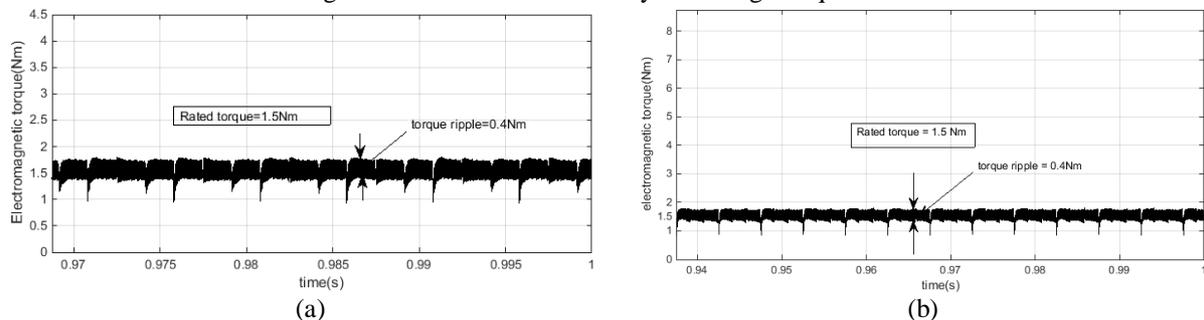


Fig. 14. Electromagnetic Torque in One-Cycle Average Torque Controlled BLDCM (a) with ON\_PWM switching (b) with PWM\_ON switching

#### IV. CONCLUSION

This paper reviews different control algorithms to reduce the torque ripple for BLDC machines with non-ideal trapezoidal back EMF. The conventional algorithms can be divided into two major categories. The first category

calculates the optimal current waveform and uses that as the current command to reduce the torque ripple. The second category uses observers to estimate the stator flux linkage and torque. All these methods need accurate information of the back EMF and rotor position. The concept of one-cycle control is used here to mitigate the torque ripple of BLDCM. In one-cycle control the average value of the switched variable follows its control reference within a switching cycle. In one-cycle average torque control the torque is controlled by controlling the input energy in one switching cycle. Here the average torque in one switching cycle is made constant. This method does not require the information of back EMF and accurate rotor position. Only one voltage sensor and one current sensor are needed to detect the DC bus voltage and current. The operation principle of the one-cycle average torque control algorithm is presented in detail. The flux linkage and electromagnetic torque behaviour in each control cycle is analyzed. It is straightforward to compute the input energy in each control cycle to implement the computation of average torque in a microprocessor. Simulation of One-Cycle control method is evaluated using matlab. Various waveforms are analyzed. The torque ripple is mitigated and its magnitude is about 0.4Nm. Commutation torque ripple with PWM\_ON switching is less as compared with the ON\_PWM switching.

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