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COMMUTATION TIME ESTIMATOR FOR PM BLDC MOTOR TORQUE SIGNATURE ENHANCEMENT

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Abstract

This paper presents the development of the commutation time estimator (CTE) for PM BLDC motor drives. The proposed scheme is aimed to enhance motor output torque by minimizing the generated torque ripples. The torque ripples originating from commutation instances cause spikes and dips in the motor output torque. The motor output torque could be enhanced by mitigating the phase current mismatch rate during phase current commutation period. This rate could be almost matched by introducing the commutation time estimator (CTE) in order to control the rate of the energized phase current to be matched with the de-energized phase rate. Results obtained have validated and verified the proposed CTE effectiveness with a 50% average reduction of the generated torque ripples in PM BLDC motor.

Keywords: PM BLDC, Motor, Torque ripples, Commutation, Estimator, Enhancement.

1. Introduction

Permanent magnet Brushless DC (PM BLDC) motors have become a very popular commercially due to their good features such as high efficiency, low maintenance, low noise, control simplicity, low weight, and compact construction. They have more gains if compared with other conventional types of AC motors in the market [1]. PM BLDC motors so far are widely used in different industrial applications and in various industrial equipment and instrumentation.

Nomenclatures

E	Back-EMF voltage (V)
I	Amplitude of the phase current (A)
i_a	Phase A motor current (A)
i_b	Phase B motor current (A)
i_c	Phase C motor current (A)
L	Self-inductance (H)
R	Phase winding resistance (Ω)
t_f	Fall time of phase current during commutation time (s)
t_r	Rise time of phase current during commutation time (s)
V_{CD}	DC Bus Voltage (V)

Abbreviations

BLDC	Brushless DC
CTE	Commutation time estimator
EMF	Electromotive force
PM	Permanent magnet
PWM	Pulse width modulation

Their small size with the ability of external rotors designs making the PM BLDC motors widely used in many applications where such properties are required such as audio equipment, computer disc drives and other consumer home and office equipment [2].

The Pulse Width Modulation (PWM) switching is one of the most common used control techniques in power electronics applications and electric drives. By adopting PWM control, it is possible to implement different types of variable speed drive applications. The PWM technique is widely implemented in single-phase and 3-phase power inverters. PWM techniques are commonly implemented in PM BLDC motor drives [3,4].

As PM BLDC motors commutate every 60 electrical degrees, the magnetic field unequally circulates and jumps every 60 electrical degrees, thereby producing uneven torque. A pulse width modulation (PWM) control algorithm for eliminating torque ripple caused by stator magnetic field jump has been proposed by [5]. His method shows that the stator magnetic field jump causes torque ripple in PM BLDC motors. Another PWM control scheme is proposed to eliminate the ripple current caused by diode freewheeling in the inactive phase of the PM BLDC motor [6]. It operates on the principle that the switch is in the PWM mode only in the beginning 30° and the last 30° zones. However, the switch is continuously turned ON in the middle 60° zone. Previous studies have discussed the different influences of four PWM modes on the commutation torque ripples in sensorless brushless DC motor. The comparative study has been conducted among four types of PWM schemes, namely, a) H_pwm-L_on, b) H_on-L_pwm, c) on_pwm, and d) pwm_on. In those studies, PWM_ON mode types have been used to reduce the commutation torque ripples [7]. The influence of the PWM mode on the current generated by back-EMF during switch-off phase in the control system of a PM BLDC motor has been discussed in [8]. The comparison has revealed that the ON_PWM type is the best among the five modes.

A PWM chopping method to improve the torque ripple for PM BLDC miniature motors is proposed in [9]. The comparison of the two proposed switching strategies to reduce the torque ripple shows that the PWM chopping method has higher output torque and lower ripples compared with the overlapping method. Previous studies [10] proposed a method using PWM_ON_PWM mode to eliminate torque ripple resulting from current emerging in the turn-off phase during non-commutation period. Also it compensated commutation torque ripples. Other PWM methods proposed in [11] based on FPGA, and an analysis study of commutation torque ripple using different PWM modes in brushless DC motors is proposed by [12]. Whereas another study [13] provides a performance analysis of the PM BLDC motor using three control strategies: square wave, PWM and hysteresis where it shows that the application of these controls is subjected to the operating conditions and load requirements.

A bridgeless cuk converter-fed for BLDC motor drive is applied in air conditioning system [14]. The proposed drive shows advantages with an improved power quality of the system. In [15], a control method is presented for a four-phase BLDC motor with non-ideal back EMF based on injecting phase currents considering the instantaneous magnitude of back-EMF. The proposed method shows a reduction of the generated electromagnetic torque ripples.

A study shown in [16] discusses the PM BLDC motor control based on rotor position sensing scheme. A PIC microcontroller is employed to generate PWM signals for driving the power inverter bridge. Parameters required for power PWM generations have been programmed, which provide flexible and online source code modifications in accordance with the motor and circuit requirements. Hardware implementation and simulation results show the effectiveness of the developed motor drive. The flexibility offered by the developed motor control and drive enables the implementation of difference control algorithms for improving the output characteristics of the PM BLDC motor. Another study based on determining the initial rotor sector and aligning the encoder with the motor was presented in [17]. The proposed algorithm has successfully reduced the vibrations and oscillations in BLDC drives.

A modified PWM switching strategy to minimize the torque ripples in PM BLDC motor based on sensored drive proposed in [18]. The scheme was implemented using a 8-bit PIC microcontroller to generate a modified PWM signals, the proposed modified PWM signals are successfully applied to the next energized phase current such that its current rise is slightly delayed or sped up during the commutation instant based on motor speed region. Results had shown that the current waveforms of the proposed PWM technique are smoother than that in conventional PWM technique. Hence, the output torque exhibits lower ripple contents and low speed oscillations. Therefore, adopting PWM control benefits in a flexible control of PM BLDC motors with an improved output drive characteristics.

2. Proposed Method

The commutation between the three-phases occurs six times per one electrical cycle. As a result, current ripple is generated in commutation periods which is the main drawback of PM BLDC motor. In the conduction region, two-phases are conducting based on position of the rotor. The rotor position is usually sensed by

Hall sensors which generate three signals corresponding to six states of rotor position. On the other hand, commutation region is the transient regions which experience the current switching from one phase into the next phase. Commutation region is relatively shorter than conduction region, and the three stator phase windings (rising phase, decaying phase, and conducting phase) are all conducted. Conduction and commutation appears 6 times per one electrical rotation of the rotor [19].

The proposed method is aimed to apply a modified PWM during an interval that is proportional to the value of the step time of the phase commutation ratio. Whereas the commutation time is much smaller compared to the total phase conduction time which is 2π/3 rads or (120°).

The value of rising and falling time where the rate of phase current for energized phase and de-energized phase are ideally matched. However, in practice, they are not matched. During high speeds, the rising time (t_r) is greater than the falling time (t_f); while at low speeds, the falling time (t_f) is greater than the rising time (t_r).

Referring to the commutation start as a reference point, the current during commutation could be expressed as:

$$i_a = I - \frac{V_{DC} + 2E}{3L} t \tag{1}$$

$$i_b = + \frac{2(V_{DC} - E)}{3L} t \tag{2}$$

$$i_c = -I - \frac{(V_{DC} - 4E)}{3L} t \tag{3}$$

At the end of commutation period, $i_a(t_f) = 0$, substituting into Eq. (3), giving the time taken for i_a to die-off (fall time) from its value $\boldsymbol{I}$ to zero will be:

$$t_f = \frac{3LI}{V_{DC} + 2E} \tag{4}$$

At the end of commutation period, $i_b(t_f) = I$, substituting into Eq. (4), giving the time taken for i_b to build up (rise time) from zero to its final value $\boldsymbol{I}$:

$$t_r = \frac{3LI}{2(V_{DC} - E)} \tag{5}$$

Referring the ideal case in which the rising time and falling time are equal, this could be taken place when: $\frac{3LI}{V_{DC} + 2E} = \frac{3LI}{2(V_{DC} - E)}$ giving

$$V_{DC} = 4E \,. \tag{6}$$

As the falling time and rising time are kept almost matched, the generated torque ripples are minimized. The rate can be matched by introducing the commutation time estimator (CTE) to control the rate of the energized phase current at high speeds by a higher duty cycle to be applied in the up-coming phase. As well as at low speed by a lower duty cycle to be generated and applied in the up-coming phase current during the estimated commutation period. The flow chart of the proposed method is given in Fig. 1.

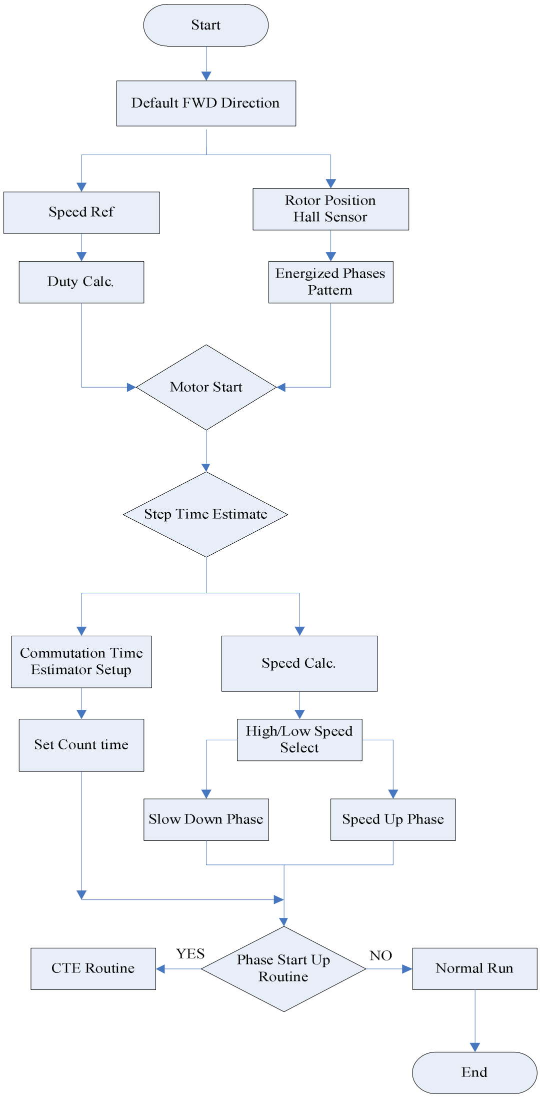


Fig. 1. Proposed CTE Method.

3. Simulation and Model

The model for PM BLDC motor drive has been built using Matlab/Simulink tool from MathWorks Inc., the models are created for the motor, the controller, motor drive and reference input to the system.

Based on the created model shown in Fig. 2, simulation results have been captured at various loading conditions. In addition, results were compared and analysed which had shown an effective reduction of generated torque ripples using the proposed CTE PWM technique.

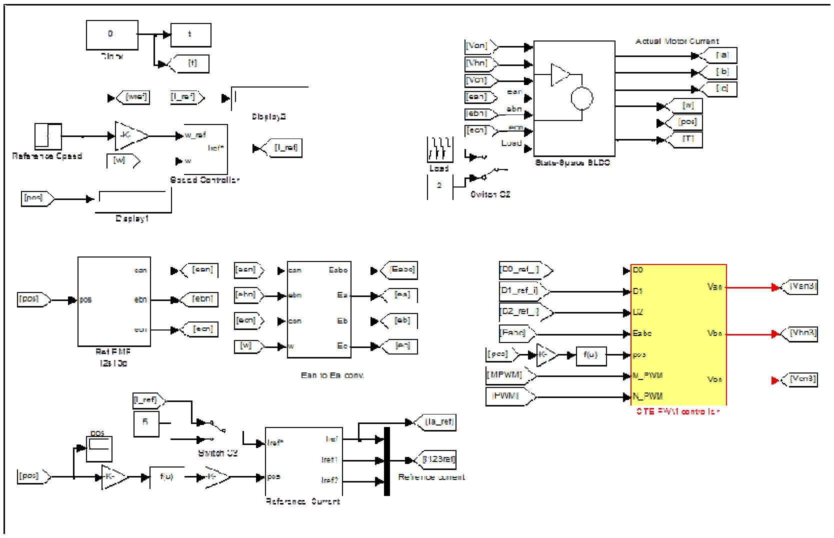
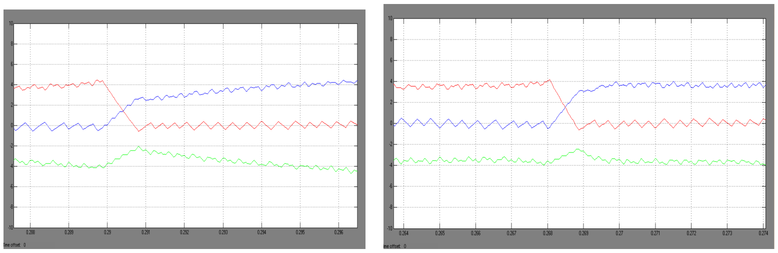


Fig. 2. PM BLDC Motor Drive Model.

4. Results and Discussions

The following waveforms shows the simulated results for the 9slots/10poles PM Brushless DC controlled using PWM controller as well as using proposed CTE PWM controller.

Figure 3 shows a comparison of three-phase currents behaviour during the commutation time when the motor operating at high-speed. As can be seen in Fig. 3(b), the rate of current rising is fairly matched with the decaying phase current when using CTE PWM switching compared to currents shown in Fig. 3(a) when using conventional PWM switching.



(a) Conventional PWM (b) Proposed CTE PWM

Fig. 3. Three-Phase Motor Currents at High-Speed (500 rpm).

The phase A current, speed, output torque and back-EMF are shown in Fig. 4 when the motor is operating at high-speed region. By comparing the waveforms with those waveforms shown in Fig. 5 obtained using conventional PWM control, it is clearly noticeable that smoother output current and smoother output torque can be achieved by using CTE PWM switching strategy.

Figure 6 shows a comparison of three phase currents behavior during the commutation time when the motor operating at low-speed. It is again very clear here that the rate of current rising is fairly matched with the decaying phase current using the proposed using CTE PWM switching.

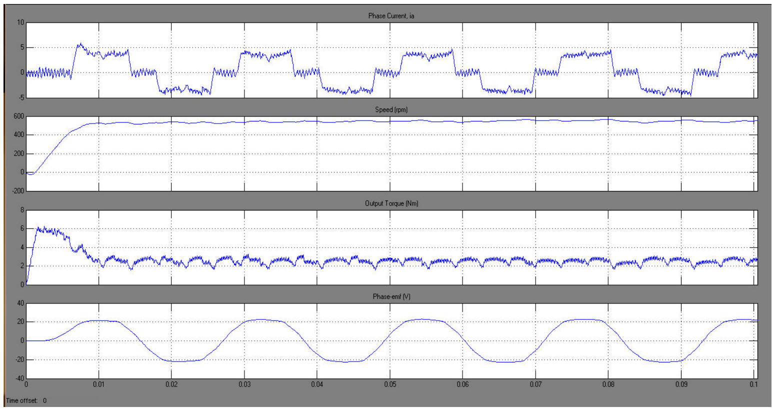


Fig. 4. Phase Current, Speed, Torque and Back-EMF Using CTE PWM Controller at high-Speed (500 rpm).

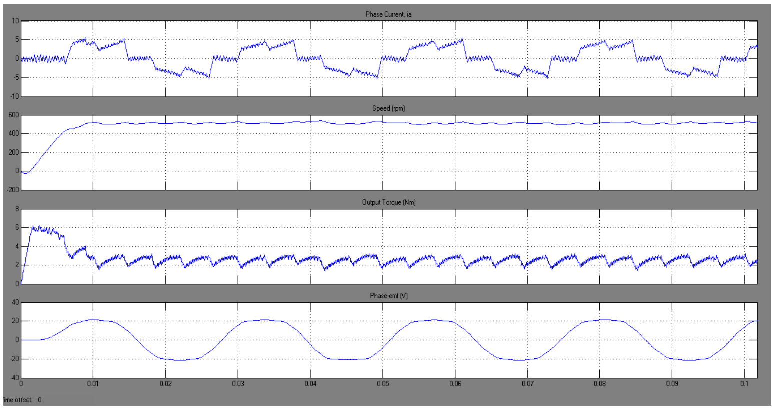
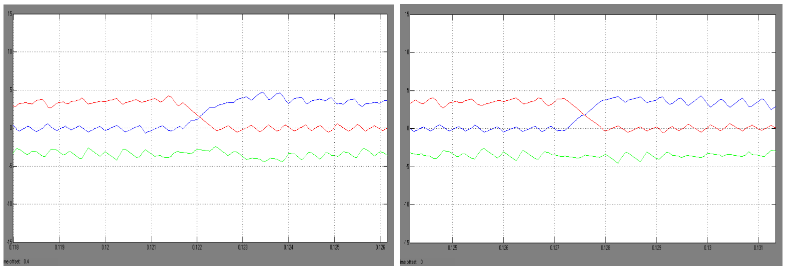


Fig. 5. Phase Current, Speed, Torque and Back-EMF Using PWM Controller at high-Speed (500 rpm).



(a) Conventional PWM (b) Proposed CTE PWM

Fig. 6. Three-Phase Motor Currents at Low-Speed (250 rpm).

Figure 7 shows the phase A current, speed, output torque and back-EMF waveforms. By comparing the waveforms with the waveforms shown in Fig. 8 using conventional PWM control, is clearly noticeable that smoother output current and smoother output torque are achievable using CTE PWM switching when the motor is operating at low-speed region.

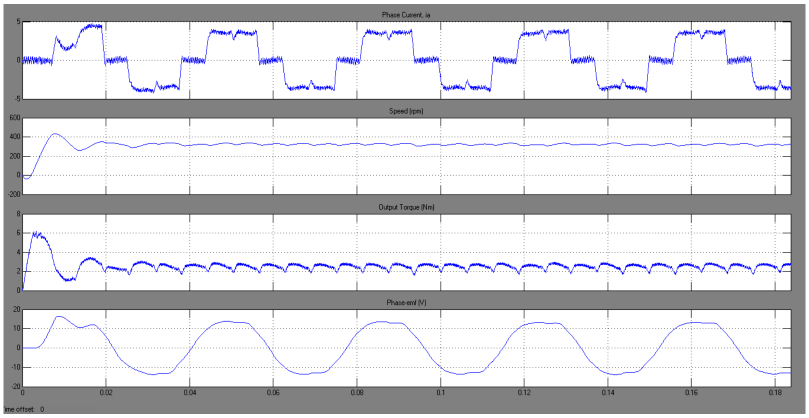


Fig. 7. Phase Current, Speed, Torque and Back-EMF Using CTE PWM Controller at Low-Speed (250 rpm).

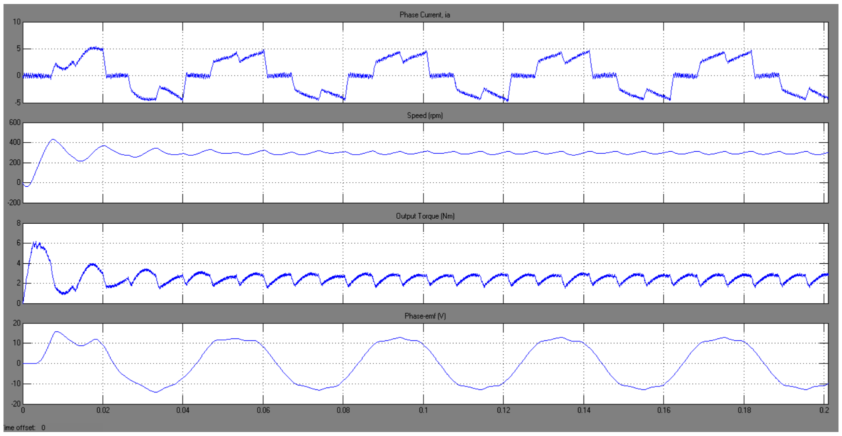


Fig. 8. Phase Current, Speed, Torque and Back-EMF Using PWM Controller at Low-Speed (250 rpm).

As observed from the Matlab/Simulink model, simulation results of the modified PWM control using CTE method show a viable smoother phase current as well as smoother output torque. In addition, the reduction of generated torque ripples has also resulted in reduction of speed oscillation.

From Matlab/Simulink results; by applying the modified PWM switching, the output average torque is increased, and a smoother output phase current is achieved. The shown model and results validate the effectiveness of the proposed technique with a visible reduction of output torque ripples.

A summary of conventional and modified PWM ripples reduction achieved is listed in Table 1. The results obtained from the commutation time estimator (CTE) strategy showing an effective reduction of the generated torque ripples with an average of about 50%.

Table 1. Comparison Summary of the Achieved Torque Ripples Reduction.

	Torque Ripples Percentage			
Speed, Load	Conventional PWM	Proposed CTE PWM	**Average Reduction**	**Percentage Reduction**
500 rpm, 2 Nm	21 %	12 %	9 %	43 %
500 rpm, 1 Nm	27 %	11 %	16 %	60 %
250 rpm, 2 Nm	28 %	11 %	17 %	60 %
250 rpm, 1 Nm	27 %	14 %	13 %	48 %

The proposed CTE control strategy has many advantages in its applications to standard PM BLDC drive system without the need for additional hardware components or hardware modification compared to other techniques reported in literature. Minimizing the generated torque ripples in PM BLDC motors has advantages in widening its application range.

5. Conclusions

This paper has presented the development of the commutation time estimator (CTE) for PM BLDC motor drives. The torque ripples in PM BLDC motor under conventional PWM switching control can be further improved by utilizing Commutation Time Estimator (CTE) method. Measurement and comparisons were addressed in terms of the motor output current, output line-line voltage and motor output torque. The measurement mainly conducted for the prototyped model PM BLDC motor. The proposed CTE method was modelled, and the results have validated the effectiveness of the proposed technique with a visible reduction of output torque ripples by 50% on average.

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