

A COMPARISON STUDY OF THE COMMUTATION METHODS FOR THE THREE-PHASE PERMANENT MAGNET BRUSHLESS DC MOTOR

Shiyoung Lee, Ph.D.
Pennsylvania State University Berks Campus
Room 120 Luerssen Building, Tulpehocken Road
Reading, PA 19610-6009

Tom Lemley, General Manager,
Gene Keohane, Director of Engineering
Moog Inc., Components Group
750 West Sproul Road
Springfield, PA 19064

Abstract: The three-phase permanent magnet brushless dc (BLDC) motor inherently needs an electronic commutation circuit to drive it because it is not a self-commutating motor. It is contrary to the conventional brush motor which commutates itself. This paper presents a comparison study of three widely used different commutation methods in terms of the complexity of the commutation circuit, torque ripple, and efficiency. The principle of the operation of the three-phase BLDC motor is introduced first and then three commutation strategies – trapezoidal (six-step), sinusoidal and field oriented control (FOC) - are discussed in detail. The characteristics of the three commutation methods are investigated intensely, and the advantages and disadvantages of each are compared to the others. The second generation MC73110 motor control chip from Performance Motion Devices, Inc. is used for experimental verification of three different commutation strategies. It makes possible to control the BLDC motor with trapezoidal commutation with Hall-effect position sensor. The sinusoidal commutation with encoder position feedback and the FOC with either Hall or encoder position feedback signal are also achievable. The experimental motor waveforms and torque ripples with different commutation methods are further investigated.

I. INTRODUCTION

The BLDC motor is a rotating electric motor consisting of three-phase armature windings on the stator and permanent magnets on the rotor, as shown in Figure 1. The mechanical structure of the BLDC motor is the conventional permanent magnet brushed dc motor (PMDCM) inside out; the rotor contains permanent

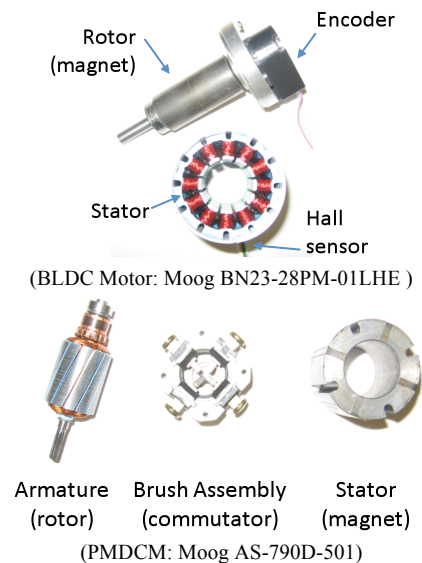


Fig. 1 Comparison of BLDC motor and PMDCM structures
(Courtesy of Moog Inc., Components Group)

magnets and the motor windings are mounted on the stator. The BLDC motor does not have brushes; those are required for commutation of PMDCM. Therefore, the maintenance-free motor drive system is possible with BLDC motor. The permanent magnets on the rotor of the BLDC motor provide a constant rotor magnetic field, and makes possible a highly efficient, high torque-per-volume, and low moment of inertia motor [1].

The BLDC motor is an electronically commutating permanent magnet DC motor [1]. Because of this motor's inherent variable speed drive nature, its applications are growing, such as its use in white goods, automobile, and machine building industries. The commutation circuit for

the three-phase BLDC motor can be implemented with discrete components or a dedicated control integrated circuit (IC). The design with discrete components provides many insights on the commutation circuit to engineers; at the same time, it requires lots of time and effort for building hardware and troubleshooting. The dedicated IC approach looks promising since little or no additional circuitry is required. Some manufacturers even offer dedicated setup software to use their IC.

In this paper the characteristics of three different commutation strategies are investigated and the experimental waveforms are demonstrated with the MC73110-based BLDC motor controller. The same motor and control electronics has been used to compare the performances of the system in three different modes of commutation.

The typical three-phase BLDC motor drive consists of a power stage with a three-phase full-bridge scheme as shown in Figure 2 and a controller that should provide three-phase PWM signals based on three Hall-effect sensors or an encoder or a resolver for the position feedback.

There are two types of permanent magnet brushless dc motors, which depend on their back-EMF waveforms. The BLDC motor has the trapezoidal (six-step) back-EMF (electromotive force) waveform. The one with sinusoidal back-EMF is called PMSM (Permanent Magnet Synchronous Motor).

The PMSM provides nearly zero torque ripples, which gives higher efficiency. The BLDC motor has 15% more power density than PMSM, assuming the copper losses are equal for both motors and the PMSM has unity power factor. For the same torque, the PMSM requires higher current handling capability [1].

The stator winding of BLDC motor is typically trapezoidally wound in order to generate the trapezoidal shape back-EMF waveform. The generated torque has a considerable torque ripple which occurs at each step of the trapezoidal (or six-step) commutation. The six-step commutation typically energizes two motor phase windings at any commutation sequence. On the contrary, the PMSM has sinusoidally distributed winding to produce the sinusoidal type back-EMF. The torque generated from the PMSM is smooth with much less ripple torque than the one with the BLDC motor. But the peak torque produce from the PMSM is lower. The sinusoidal commutation yields the sinusoidal motor current by energizing all three motor windings.

The differences between the BLDC motor and the PMSM are summarized in Table 1 [5, 6].

Table 1. Comparison of BLDC and PMSM

	BLDC	PMSM
Winding Distribution	Trapezoidal	Sinusoidal
Energized Phase	Two Phases	Three Phases
Back-EMF Waveform	Trapezoidal	Sinusoidal
Torque Strength	Strong	Weak

A simplified three-phase full-bridge power circuit for BLDC motor is shown in Figure 2. The relationships between three-phase back-EMF, motor current, and air-gap power of the BLDC motor are shown in Figure 3 [2]. The trapezoidal back-EMF (e_a , b , and c) has a constant magnitude of E_p during 120 electrical degrees in both positive and negative half cycle. The air-gap power, P_a , and the electromagnetic torque are both continuous when applying motor current i_a , b , and c during the same period in both half cycles.

The instantaneous voltage equation and torque equations of a BLDC motor from Figures 2 and 3 are [1]

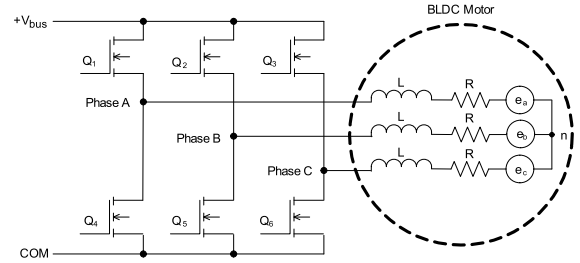


Figure 2. Three-phase full-bridge power circuit for BLDC motor drive

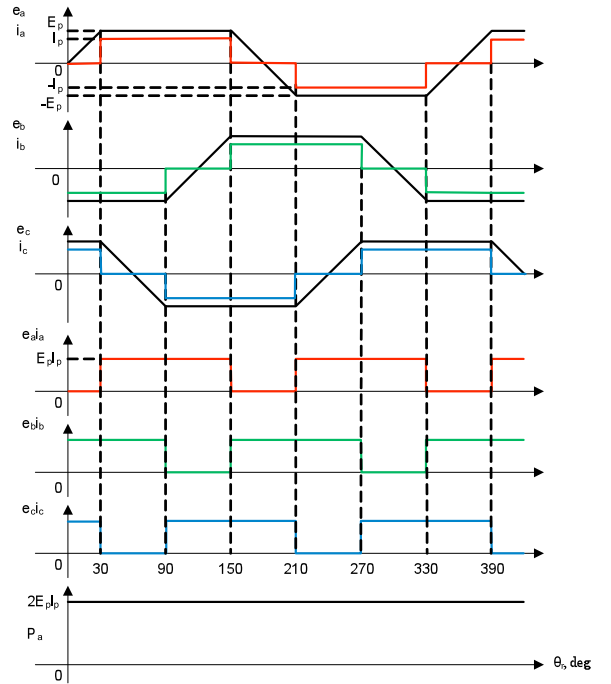


Figure 3. Relationship between back-EMF, motor current, and air-gap power for three-phase BLDC motor drive

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

$$T_e = \frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_m} \quad (2)$$

where, $v_a, b \text{ and } c$: motor terminal voltages, V
 $i_a, b \text{ and } c$: motor phase currents, A
 $e_a, b \text{ and } c$: back-EMF voltages, V
 R : motor winding resistance, Ω
 L : motor winding inductance, H
 ω_m : motor angular speed, rad/s
 T_e : motor torque, $N \cdot m$

The motor torque is generated by the sum of products of back-EMF and motor current as shown in Figure 3 and equation (2). However, it is inversely proportional to the motor speed, yielding high torque at low speed and low torque at high speed.

II. COMMUTATION STRATEGIES

In order to drive the BLDC motor, an electronic commutation circuit is required. This paper deals with the position sensor-based commutation only. The widely used commutation methods for the BLDC motor are trapezoidal (or six-step), sinusoidal, and field oriented control (FOC) (or vector control). Each commutation method can be implemented in different ways, depending on control algorithms and hardware implementation to provide their own distinct advantages.

A. Trapezoidal Commutation

The Hall-effect sensor is the most cost effective way of rotor position sensing. The timing diagram of three typical Hall sensors with 120° angle separation is shown in Figure 4. The experimental waveforms of three Hall signals in both clockwise (CW) and counterclockwise (CCW) directions of motor rotation are shown in Figure 5. The direction of rotation is viewed at the motor shaft. The sequences of the Hall signals are Hall A-Hall B-Hall C in CW and Hall B-Hall C-Hall A in CCW direction.

The trapezoidal (six-step) commutation makes two switching power devices on each motor phase in a predetermined sequence. This method is very popular because of the simplicity of its control algorithm. It uses a six-step sequence using three Hall-effect sensors to get rotor position information. It is very effective at controlling motor speed, but suffers from torque ripple during commutation, especially at low speed. Therefore, it is popular for low-end applications requiring simple

closed-loop operation. But there is significant torque ripple generated from the non-linearities in the commutation scheme, because only two motor windings carry current at any given time. The non-linearities generate noise and vibration. The current controller must be slow enough so that it does not react to the transients from the current transfer from phase to phase; thus, it limits the performance. In order to generate high torque with trapezoidal commutation, the 180° commutation method should be chosen, but the 120° commutation provides minimum torque ripple.

The six operational modes are shown in Figure 6 with 120° commutation strategy with Hall-effect position feedback sensor. Each section has a 60° interval in order to conduct two motor phases at the same time. The switching sequence is determined to conduct two motor phases consecutively as the motor spins [2].

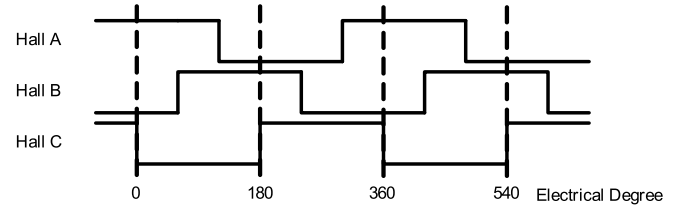
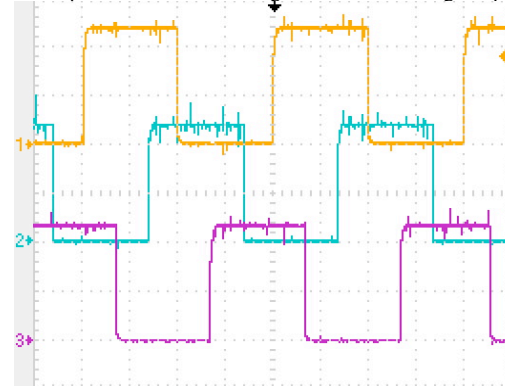


Fig. 4 Three-phase Hall sensor timing chart with 120° angle separation



(a) CW direction



(b) CCW direction

Fig. 5 Measured Hall signals in CW and CCW direction at 1500r/min
(CH1: Hall A, CH2: Hall B, CH3: Hall C)
(Vertical: 2V/div, Time: 5ms/div)

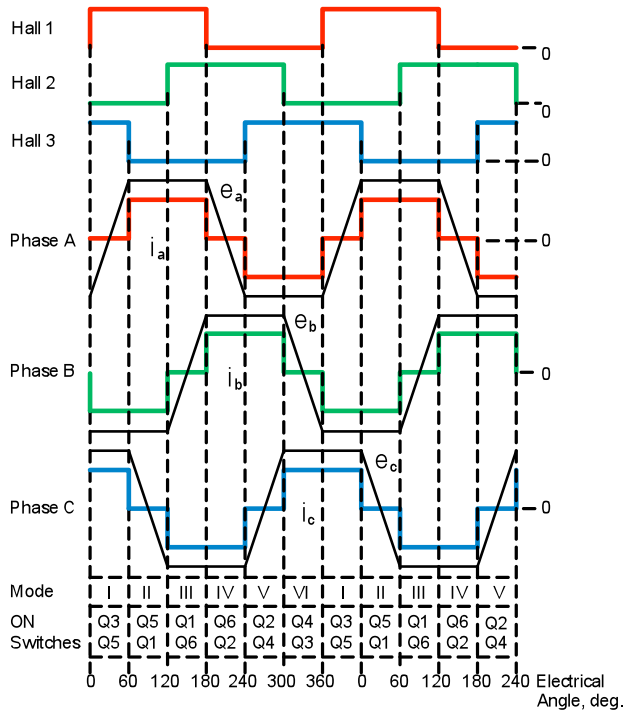


Fig. 6 Trapezoidal (six-step) commutation with Hall sensors

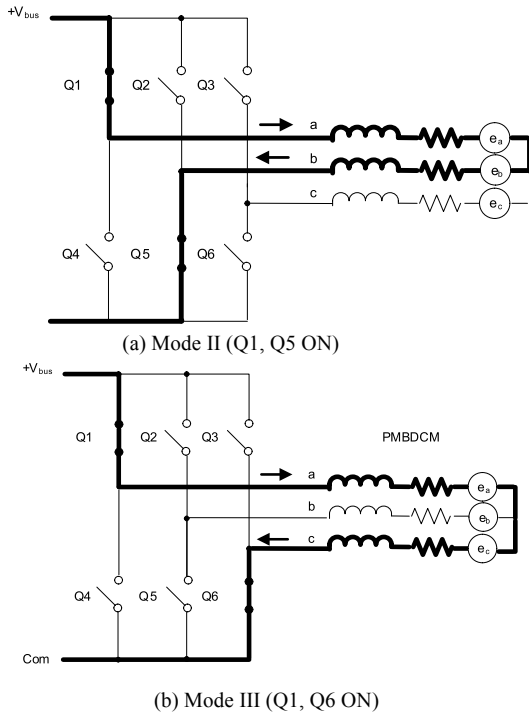


Fig. 7 Equivalent circuit examples of two operational modes

B. Sinusoidal Commutation

The sinusoidal drive scheme replaces the flat peak of the trapezoid with a sinusoidal waveform that matches more closely the back-EMF. It is necessary to overlap the commutation of phases, selectively firing more than one pair of power switching devices at a time. It can be

operated as an open- or closed-loop configuration using a speed feedback sensor and is typically used in midrange performance applications requiring speed and torque control.

Figure 8 shows a simplified block diagram of a sinusoidal commutation scheme with the MC7310 motor control IC [3]. The sinusoidal lookup table provides two sinusoidal motor phase current command signals. In addition to the encoder, the Hall-effect sensors are required for initializing sinusoidal commutation. The sinusoidal commutation modulates the three-phase motor currents which produces smooth and precise motor control. It also eliminates the torque ripple and non-linearities in motor current, which occur inherently with the six-step commutation.

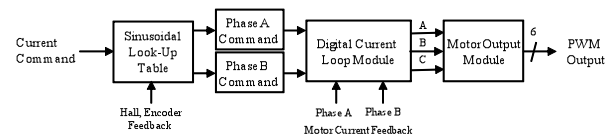
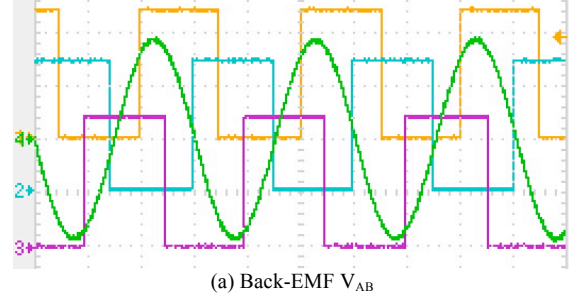
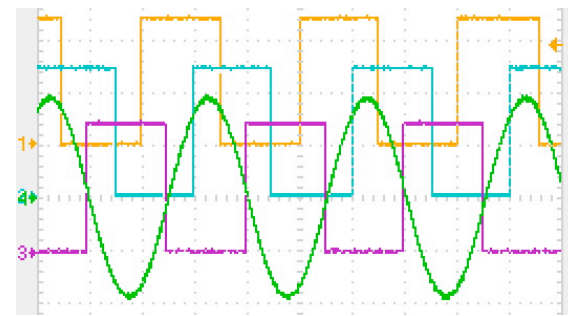


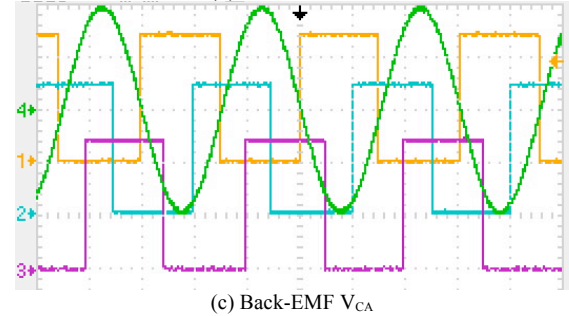
Fig. 8 Simplified block diagram of a sinusoidal drive scheme



(a) Back-EMF V_{AB}



(b) Back-EMF V_{BC}



(c) Back-EMF V_{CA}

Fig. 9 Measured Hall signals and sinusoidal back-EMF waveforms. (CH1: Hall A, CH2: Hall B, CH3: Hall C, CH4: Back-EMF) Vertical: 2V/div(CH1,2,3) 2.5V/div(CH4), Time: 5ms/div

The sinusoidal commutation requires high resolution position feedback devices, such as optical encoder or resolver. This makes the sinusoidal commutation more expensive than the six-step commutation. But it provides reduced torque ripple and allows precise control.

Figure 9 shows the measured Hall signals and the back-EMF waveforms of the PMSM (Moog BN23-28PM-01LHE). The back-EMF V_{AB} is in phase with the inverse of the Hall B waveform. In the next image, back-EMF V_{BC} is in phase with the inverse of Hall C. Finally, the back-EMF V_{CA} is in phase with the inverse of Hall A. The proper commutation logic with the rotor position information provides correct switching sequences of the power switching devices.

C. Field Oriented Control

The FOC is suitable for the high-end application due to its complex design and higher processing requirements. It commutates the motor by calculating voltage and current vectors based on motor current feedback. It maintains high efficiency over a wide operating range and allows for precise dynamic control of speed and torque.

The FOC controls the stator currents represented by a space vector [5, 6]. It transforms three-phase stator currents into a flux generating part and a torque generating part and controls both quantities separately. The arrangement of the FOC controller resembles a separately excited DC motor. The simplified block diagram of a FOC is shown in Figure 10 [3].

The various reference frame transformations in FOC are shown in Figure 11 [6]. The Clarke transformation converts the three-phase sinusoidal system (A, B, C) into a two-phase time variant system (α , β). A two-coordinate time invariant system (d, q) is obtained by the Park transformation. In this system, the motor flux generating part is d (direct) and a torque generating part is q (quadrature).

The space vector modulation (SVM) provides more efficient use of the bus voltage than the conventional sinusoidal pulse width modulation (SPWM) technique.

The maximum output voltage based on the SVM is 1.15 times bigger than the conventional SPWM. The SVM considers the power circuit as one device which affects all six power switching devices because it controls the voltage vector [6].

The characteristics of three different commutation methods for the BLDC motor and PMSM are summarized in Table 2 [7, 8].

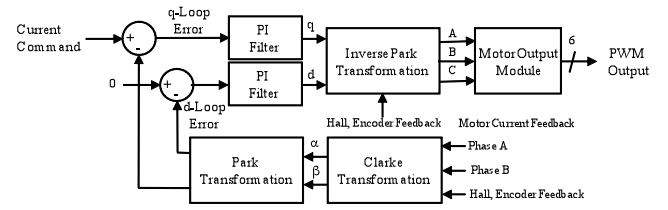


Fig. 10 Simplified block diagram of a FOC

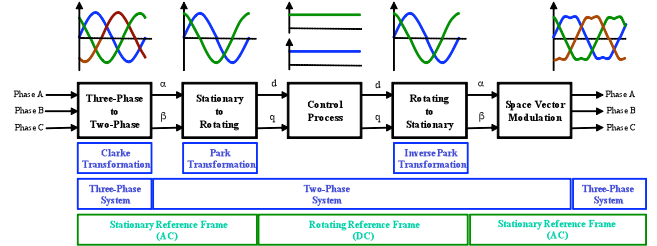


Fig. 11 Various coordinate transformations in FOC system

Table 2. Characteristics of commutation methods for the BLDC motor and PMSM

Commutation Methods	Speed Control	Torque Control		Required Feedback Devices	Algorithm Complexity
		Low Speed	High Speed		
Trapezoidal	Excellent	Torque Ripple	Efficient	Hall	Low
Sinusoidal	Excellent	Excellent	Inefficient	Encoder, Resolver	Medium
FOC	Excellent	Excellent	Excellent	Current Sensor, Encoder	High

III. COMPARISON OF GENERATED TORQUE RIPPLES WITH SIMULATION AND EXPERIMENTAL VERIFICATION

A. Verification with Simulation

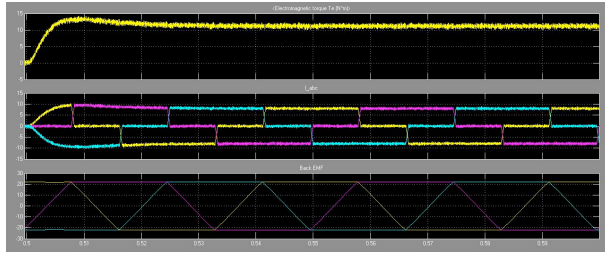
In order to verify the generated torque ripples with various combinations of two motor types and three different commutation strategies, simulation results with MATLAB/Simulink software is shown in Figure 12.

The simulation results verify that mismatch of the back-EMF waveform and commutation method produces ripple rich torque. Therefore, the BLDC motor and trapezoidal (six-step) commutation and the PMSM and sinusoidal commutation are the most desirable combination to produce minimum torque ripple.

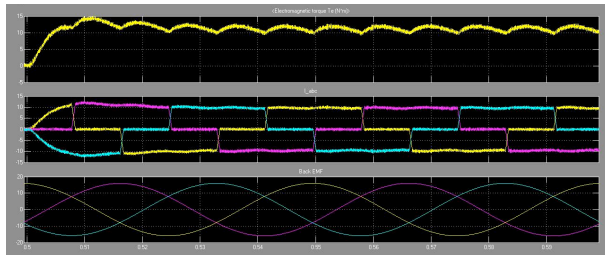
B. Experimental Verification

The experimental verification was performed with the MC73110 Developer's Kit from Performance Motion Devices, Inc.

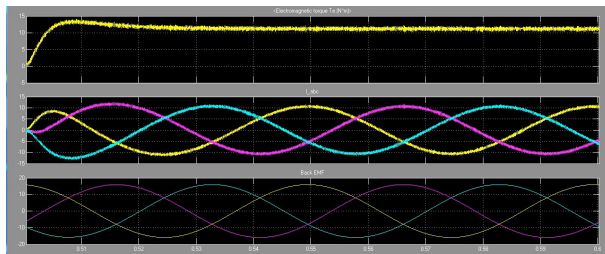
The MC73110 motor control IC has developed into an advanced single-chip, single-axis device that can be used



(a) Trapezoidal commutation with BLDC



(b) Trapezoidal commutation with PMSM



(c) Sinusoidal Commutation with PMSM

Fig. 12 Simulation results of different combination of commutation strategies and motor type
(Top) Torque (Center) Motor current (Bottom) Back-EMF

to implement an intelligent three-phase BLDC motor controller based on FPGA and ASIC technologies [3]. It is packaged in a 64-pin thin quad flat pack (TQFP) measuring 12 mm by 12 mm and operates on 3.3V. It can be operated in internal velocity profile mode, velocity mode with an external analog, digital velocity command signal, or torque mode with an external torque command signal. It also can be operated as a standalone controller using pre-programmed parameters stored onto chip flash memory or through the RS-232 serial port using the Pro-Motor GUI setup software. The simplified functional block diagram of the MC73110 is shown in Figure 13.

The various functions useful for the development of the BLDC motor drive are embedded in the MC73110 IC. These functions include, for example: the three-phase PWM generation for three-phase full-bridge power circuit and three-signal PWM for single switch per phase power circuit configuration, Hall- or quadrature encoder-based commutation, digital current and velocity loops, profile generation, emergency stop, analog velocity command, and RS-232 serial communication port. In addition to the conventional six-step with Hall-effect sensors and sinusoidal commutation with encoder, FOC is possible

with MC73110 IC V2.2G and Pro-Motor V2.51. There are four possible commutation methods as listed below:

- Hall-effect sensor based trapezoidal commutation
- Encoder-based sinusoidal commutation
- Hall-effect sensor based FOC
- Encoder-based FOC

A quadrature encoder and three Hall-effect sensors together are required to implement the sinusoidal drive. The FOC drive can be realized by either a quadrature encoder or three Hall-effect sensors.

The experimental setup to verify three different commutation methods is shown in Figure 14. The tested motor was PMSM (Moog BN23-28PM-01LHE) and the motor terminal voltage and motor current waveforms of both trapezoidal (six-step) and FOC drives are shown in Figures 15 and 16.

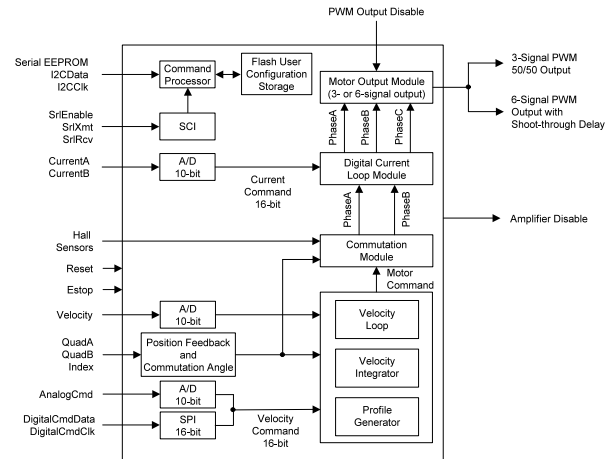


Fig. 13 Simplified functional block diagram of MC73110 motor control IC

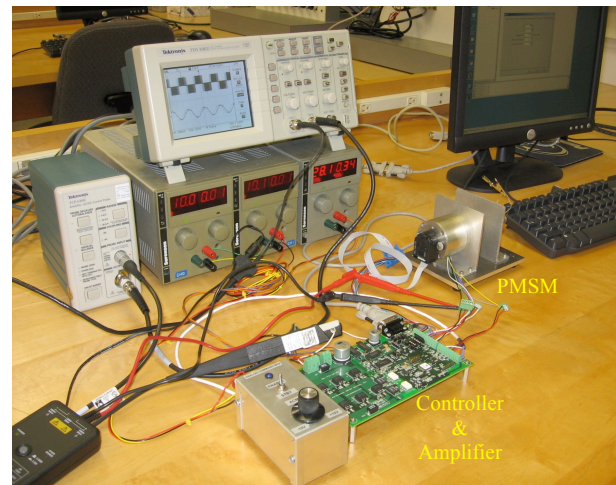


Fig. 14 Experimental setup for commutation strategies

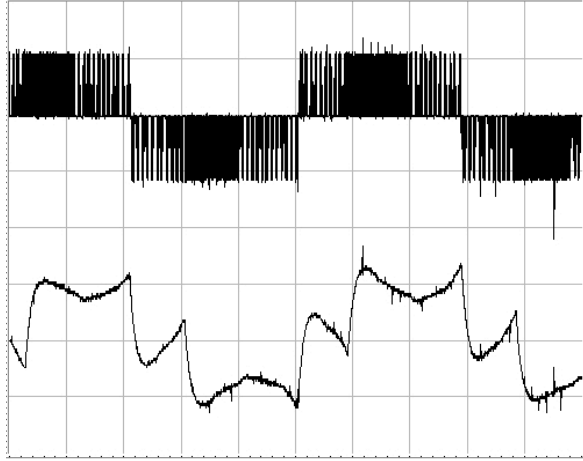


Fig. 15 Relationship between motor line-to-line voltage (Top: 25V/div) and line current (Bottom: 0.5A/div) with six-step commutation

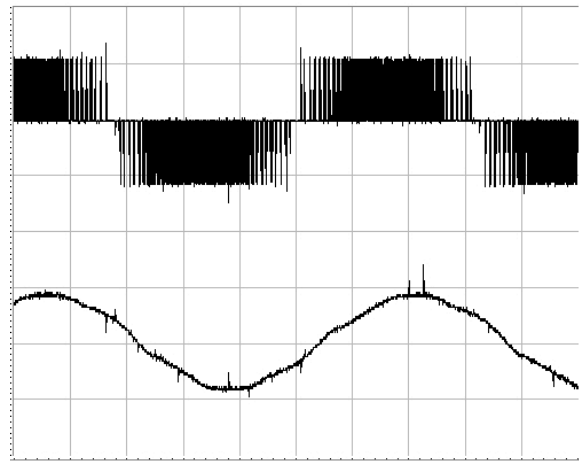


Fig. 16 Relationship between motor line-to-line voltage (Top: 25V/div) and line current (Bottom: 0.5A/div) with FOC commutation

The Hall-effect sensor-based trapezoidal drive and FOC drive provide a similar six-step current waveform as shown in Figure 15. In other hand, encoder-based sinusoidal drive and FOC drive show sinusoidal motor current waveform as shown in Figure 16. The line-to-line motor terminal voltages are look similar with both commutation methods. The fast Fourier transform (FFT) of voltage waveforms may reveal the difference between two.

IV. CONCLUSIONS

Three different commutation strategies are compared, and their characteristics are investigated in this paper. The trapezoidal commutation generates torque ripples at low speeds and is relatively efficient in the high speed range.

The sinusoidal commutation provides smooth operation at low speeds, but it is inefficient in high speed range. The FOC gives the best of both trapezoidal and sinusoidal commutations – smooth operation at low speed and efficient running at high speed. The torque ripple can be significantly reduced by matching the motor type with the commutation strategy. The adequate combinations for producing minimum torque ripple are the BLDC motor with the six-step commutation and the PMSM with the sinusoidal commutation. The FOC can apply to both types of motor to get the best drive performances, but it may require extra code development and hardware components. The motor current waveforms are sinusoidal with both the sinusoidal and the FOC commutation cases.

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