# Influence of PWM Schemes and Commutation Methods for DC and Brushless Motors and Drives

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**ABSTRACT**: Currently, many different types of dedicated PWM motor control IC's are available in the market to control DC and brushless DC motors. Unfortunately, switching schemes of these IC's are either fixed or limited in flexibility, resulting in higher noise and poor efficiency in many cases. In this article, more than 5 different switching schemes are presented and relative advantages and drawbacks of each mode are compared. It was found that selection of the switching scheme affects performance characteristics such as current ripples in DC link, line current harmonics, and losses in the motors and drives. Based on the motor parameters and application requirements, selection of optimal switching scheme and PWM frequency can improve operating efficiency and motor/drive sizing. In addition, a simple DSP-based programmable brushless motor controller design capable to select any one of the above 5 switching schemes or Hall sensor-based sinusoidal scheme is demonstrated.

## I. INTRODUCTION

Permanent magnet DC and brushless motors [1] are gaining popularity in diverse applications from appliance and automotive to medical and military products, due to its compactness, high efficiency and low cost. Currently, several semiconductor manufacturers produce dedicated PWM motor control IC's targeted to control these motors. It was found that the switching schemes of these chips are either fixed or limited in flexibility, resulting in high noise and poor efficiency in many cases. In fact, several different PWM switching schemes are possible for motor control applications. In this article, 5 different switching schemes, which encompass most of the currently available techniques, will be introduced. Characteristics and relative advantages and drawbacks of each scheme will be discussed in detail. Several performance concerns and designs that may be affected by the selection of the PWM scheme include:

Operating system efficiency

Sizing of bus capacitor due to the amount of ripple current in DC link

PWM noise and EMI from line current ripple

Drive losses that lead to sizing and cooling issues

Motor losses due to core loss and ripple torque

This paper will discuss how the selection of the switching scheme influences the above characteristics. Unlike dedicated motor control chips, a flexible motor controller based on motor control DSPs can select one of the preprogrammed switching schemes for optimal power stage design and operation.

Unlike general purpose 6-step drives mentioned above, high performance servo systems used in machine tools, factory automation and document handling applications require sophisticated motor drives controlled by micro-controllers or DSPs. It has been known in the industry that performance characteristics (for instance, efficiency and torque ripple) of a motor driven from a conventional 6-step drive, in general, is different from those of sinusoidal servo drives. The major difference is due to the resolution of feedback and phase current waveform. Poor resolution of Hall sensor feedback, typical in 6-step drives, cannot produce sophisticated sinusoidal-like waveform. Compared to sinusoidal drives, 6-step drives tend to produce high torque ripple and audible noise. Another typical difference lies in current sensors. Typical sinusoidal servo drives adopt phase current control on each phase based on measured phase currents. Compared to bus current control, used in typical 6-step drives, phase current controlled drives exhibit higher dynamic performance and high torque at high speeds. An alternative method to control phase currents is the synchronous regulator [3], in which control is applied is the synchronous reference frame. One of the major advantages of this method is that it eliminates steady-state current phase lag and improves high speed efficiency and torque capability. In conventional phase current control, phase advance technique is often used to compensate for the lagging current. Refer to [4,5] for detailed description of current control issues. Recently, with DSP-based angular position estimation technique, it became possible to produce sinusoidal-like current waveform with mere Hall sensor feedback. This technique is another cost-effective way of improving operational performance of the drive system with commonly available sinusoidal BEMF motors. Load test results in Appendix A include data for these current control methods and are compared in the discussion.

## II. SWITCHING SCHEMES

Most DC and brushless motor drives take switch configurations shown in Fig. 2.1, although simpler configurations such as unipolar drives may be adopted in some cost-sensitive, small motors. In this diagram, semiconductor switches (Sa, Sb…) are either MOSFETs or IGBTs along with anti-parallel diodes. Each phase terminal is connected to a pair of switches as shown and the potential of each phase terminal may have one of the three conditions: (a) High (top switch on, bottom switch off), (b) Low (top switch off, bottom switch on) or (c) OFF (both switches are off). When both switches in the same phase are on, the bus voltage is short-circuited (called “shoot-through condition”). This condition should be inhibited at all times. To eliminate shoot-through during switching transients, a small dead-time (usually 100 ns – 3 μs) is introduced in between turn-off of one switch and turn-on of the other switch in the same phase.

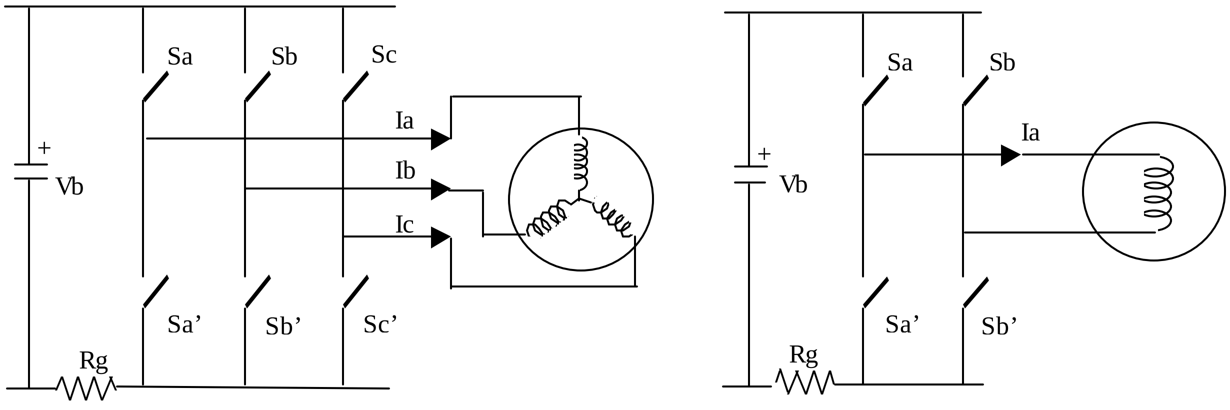
When brushless motors are controlled by the 6-step mode, one phase is OFF for two 60 degree periods in an electrical cycle as shown in Fig. 2.2B. Since only two phases are active at any given time, switching activities can be analyzed by using the simplified configuration of an equivalent DC motor as shown in Fig. 2.1B, neglecting the third phase in off condition. In fact, discussions in this article except commutation issues can directly be applicable to brushed permanent magnet DC motors.

In DC motors and brushless motors, the switching state during a PWM period takes only one of the following 4 possible states:

(1) D: Driving (One phase is high, while the other phase is low)

(2) Sh: Short circuit to High (Two phases are shorted to high side bus)

(3) Sl: Short circuit to Low (Two phases are shorted to low side bus)
(4) R: Regeneration (One phase is high, while the other phase is low)



(A) Brushless motor (B) DC motor

Fig. 2.1 Switch configuration of drives

The difference between D (Driving) state and R (Regeneration) state is that power flows from DC link to the motor in D state, while the direction of power flow is reversed in R state. Example of these states will be shown later during the discussion of switching schemes. Note that for plots of Fig. 2.2-2.7 to be discussed in the following, PWM switching frequency of each mode is fixed to 20 kHz and oscilloscope channels indicate:

Analog Channel A2: A-phase line current (1A = 100mV)
Digital channel 0: PWMAH/ (Sa)
Digital channel 1: PWMBH/ (Sb)
Digital channel 2: PWMCH/ (Sc)
Digital channel 3: PWMAL/ (Sa')
Digital channel 4: PWMBL/ (Sb')
Digital channel 5: PWMCL/ (Sc')

A logic low (ground) signal on a digital channel indicates an active (on) power switch. Plots in Figs. 2.2A-2.7A are taken from a brushed DC motor, while a brushless motor is used to get plots of Figs. 2.2B-2.7B.

A. PWM Scheme 0 (2 Quadrant switching).

In this scheme, positive A-phase voltage is applied by permanently tuning on Sb' while switch Sa will be pulse-width modulating. When both Sa and Sb' are on (D state), current Ia increases. Motor current during the PWM off period is free-wheeling (slowly decaying due to resistance of the winding and semiconductor switches) through an anti-parallel diode of Sb and the conducting transistor Sa (Sh state). For rotation in the reverse direction, negative A-phase voltage is applied by permanently tuning on Sa' while modulating switch Sb. Only two switchings occur in a PWM period. The switching sequence required in one PWM period to produce 30% of the bus voltage is

Sl(70%) ~ D(30%)

In this example, only high side switches are modulated. A similar result will occur when only low side switches are modulated. In this scheme, the bus capacitance requirement is small and switching losses are very low. One major drawback is that the motor cannot change direction quickly (2-quadrant operation). It relies on mechanical friction to decelerate. Fig. 2.2A indicates 20 mV peak-to-peak current ripple (equivalent to 0.2A ripple). A macro view of a brushless motor current for approximately 2 electrical cycles is shown in Fig. 2.2B. Thick black plots on digital channels of this and the subsequent figures indicate active PWM.

B. PWM Scheme 1 (4 Quadrant switching, Simultaneous).

In this scheme, positive a-phase voltage is applied by pulse width modulating Sa and Sb' simultaneously. When both Sa and Sb' are on (D state), current Ia will increase as in scheme 0. Motor current during the PWM off period decays rapidly through two anti-parallel diodes of Sa' and Sb, and reverse application of bus voltage (R state). For rotation in the reverse direction, negative A-phase voltage is applied by modulating Sa' and Sb.

In this scheme, two simultaneous switchings of two transistors occur in a PWM period. The switching sequence to produce 30% of the bus voltage is

R(35%) ~ D(65%),

resulting in net application of positive bus voltage for 30% (65% - 35%) of the period. In this scheme, bus capacitance requirements are very large and switching losses are also high. One major advantage over Scheme 1 is that the motor can operate in 4-quadrant. Fig. 2.3A indicates 32 mV peak-to-peak current ripple. A macro view of brushless motor currents for about 2 electrical cycles is shown in Fig. 2.3B. Due to rising bus voltage during regeneration in this and all subsequent switching schemes that enables 4-quadrant operation, , a shunt regulator or power supply with bi-directional power flow should be used.

C. PWM Scheme 2 (4 Quadrant switching, Simultaneous, Complementary).

This mode operates similarly to scheme 1 above, except that the switching states of Sb and Sa' are complementary to Sa and Sb'. This method has two distinct differences over scheme 1. First, it allows the current to change direction within a given PWM period. This offers finer current control around zero current. Another difference is that when MOSFET switches are used, the current during R state can be flown through MOSFETs instead of the anti-parallel diode to possibly achieve lower conduction loss. This technique is called "synchronous rectification" and used in many MOSFET-based power converters [2]. By using MOSFETs with low conduction resistance, conduction losses can be reduced to less than that of the diode alone. Fig. 2.4A shows current ripple similar to scheme 1. A macro view of brushless motor currents for approximately 2 electrical cycles is shown in Fig. 2.4B.

D. PWM Scheme 3 (4 Quadrant Non-Simultaneous)

This scheme is similar to PWM Scheme 1 except that the switching on each phase occurs at different times. We might notice that the switching of Sb' is that of Sa delayed by one half of a PWM period. A total of four switchings occur in a PWM period and the switching sequence to produce 30% of the bus voltage is

Sl(35%) ~ D(15%) ~ Sh(35%) ~ D(15%),

resulting in a net application of positive bus voltage for 30% of the period. Regeneration can occur when the duty of Sa is less than 50%. To produce regeneration for 30% of the time,

Fig. 2.2. PWM Scheme 0

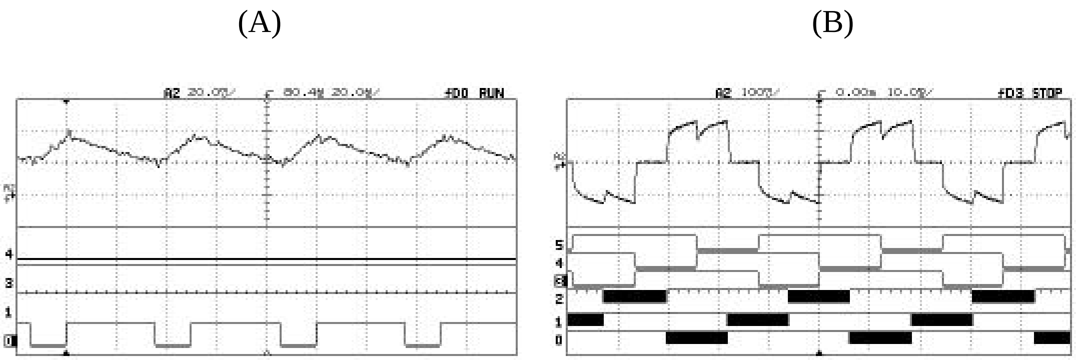

(A) (B)

Fig. 2.3. PWM Scheme 1

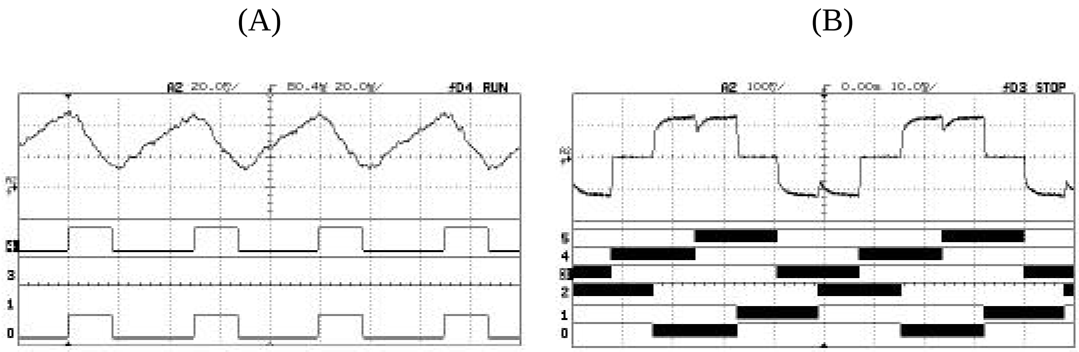
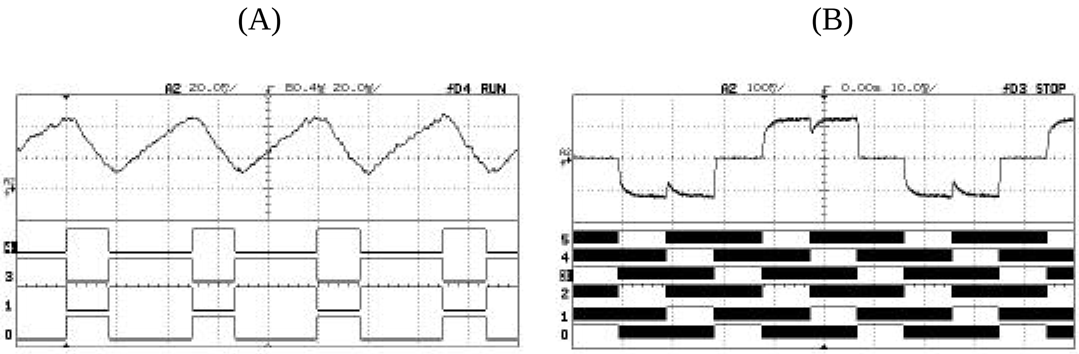

(A) (B)

Fig. 2.4 PWM Scheme 2


(A) (B)

Sl(35%) ~ R(15%) ~ Sh(35%) ~ R(15%).

Due to non-simultaneous switching, the frequency of current ripple is two times that of the switching frequency. Current ripple and PWM noise are very low in this switching scheme.

Full 4-quadrant operation is possible with this scheme. Fig. 2.5A shows very small current ripple compared to scheme 1. A macro view of brushless motor currents for about 2 electrical cycles is shown in Fig. 2.5B.

Fig. 2.5 PWM Scheme 3

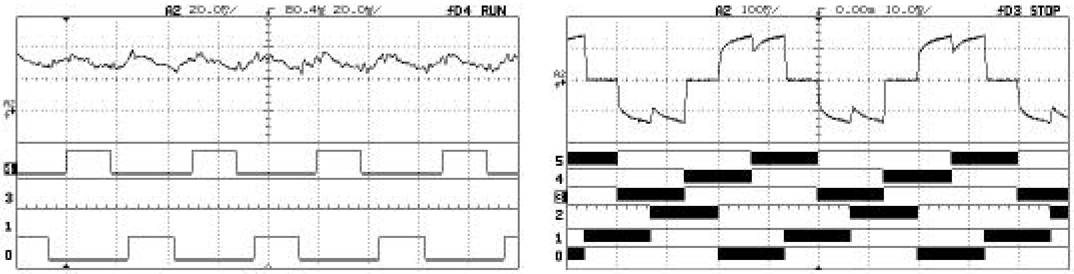

(A) (B)

Fig. 2.6 PWM Scheme 4

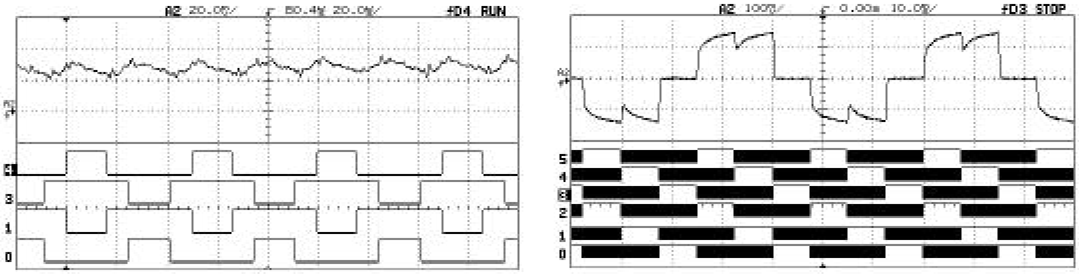
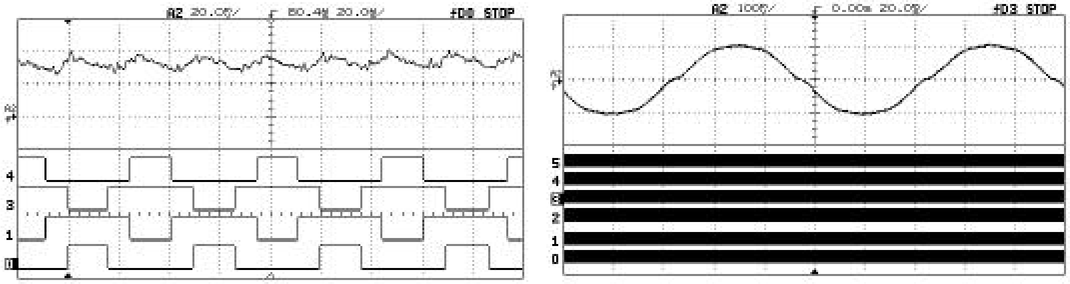

(A) (B)

Fig. 2.7 Sinusoidal PWM


(A) (B)

E. PWM Scheme 4 (4 Quadrant Non-Simultaneous, Complementary).

This mode operates similarly to scheme 3 above, except that the switching states of Sb and Sa' are complementary to Sa and Sb'. As discussed in scheme 2, conduction losses in MOSFET drives can be reduced, and current control at around zero current is superior to scheme 3. In fact, switching scheme 4 is very similar to the PWM waveforms of sinusoidal PWM as shown in Fig. 2.6A and 2.7A.

## III. DISCUSSIONS

In most dedicated brushless motor control chips, the switching scheme is either fixed to scheme 0, or selectable from two schemes (scheme 0 or 1). The following table summarizes available switching schemes of popular brushless control chips.

| Part Number | Switching scheme |
|---|---|
| Motorola MC33035/33033 | Scheme 0 |
| Hitachi ECN3030/3035 | Scheme 0 |
| TI UC3625/UCC3626 | Scheme 0 or 1 |
| Vishay Siliconix Si9979 | Scheme 0 or 1 |
| Allegro A3932 * | Scheme 0, 1 or 2 |

* Under development. Not available in the market at the time of writing

Currently, no dedicated control chips offer schemes 3 and 4. However, PWM schemes 3 and 4 can be implemented by additional hardware circuits on the motor control chips or by using a DSP design. The MCB2406 motor control board from Drivetech is designed to demonstrate generation of all of the above switching schemes. The user can select one of 5 different switching schemes for target application. This 2.5"x3.5" piggy-back control board shown in Fig. 3.1 is based on TMS320LF2406 (TI) DSP. In addition, the software can also be configured for various sinusoidal operation such as simulated sinusoidal operation from Hall sensor feedback, phase current controlled sinusoidal operation and synchronous regulator control with encoder feedback.

All load test data for 3 different motors ( 2 brushless, and 1 brushed motors) shown in Appendix A were controlled from MCB2406 with different configurations. The PWM frequency was fixed to 20 kHz at all times. Efficiency is calculated from motor output power and DC supply input voltage times current. Based on analysis of the measurement data, we can observe the following facts regarding switching schemes.

1. When 2-quadrant operation is enough to meet the performance goal (such as fans and pump application), scheme 0 offers the most cost effective and efficient solution among 5 switching schemes.

2. Compared to schemes 1 and 3, schemes 2 and 4 (complementary switching) can be advantageous in terms of conduction loss (when the synchronous rectification using MOSFETs are utilized) and fine current control. For MOSFET drives where synchronous rectification is advantageous (conduction loss in the MOSFET is lower than that of the diode), schemes 2 and 4 will always result in higher efficiency.

3.  For low inductance high current motors, where PWM current ripple is pronounced, efficiencies of the system with split switching schemes (schemes 3 and 4) are superior to simultaneous switching schemes (scheme 1 and 2).  Possible examples include battery operated motors (power tools), automotive motors, slotless motors, etc.  Preliminary test data show that selection of an appropriate switching scheme may greatly improve total power loss (loss in motor and drive).  Since the magnitude of the PWM ripple current depends only on the supply voltage and the motor inductance, efficiency at low speeds and light loads can be significantly improved.  For higher power, lower inductance motors, the efficiency improvement can be much higher.  On the other hand, high inductance motors may prefer simultaneous switching schemes to reduce switching losses at the drive.

4.  In simultaneous switching schemes (schemes 1 and 2), power flows back and forth between DC link and the motor repetitively.  This characteristics demands higher bus capacitance and a lower ESR.  These schemes are likely to produce higher EMI.  For all other schemes, a free wheeling (Sh or Sl) state is introduced after an active D or R state.

5.  Switching scheme 4 is very similar to sinusoidal operation except that it still uses 6-step commutation.

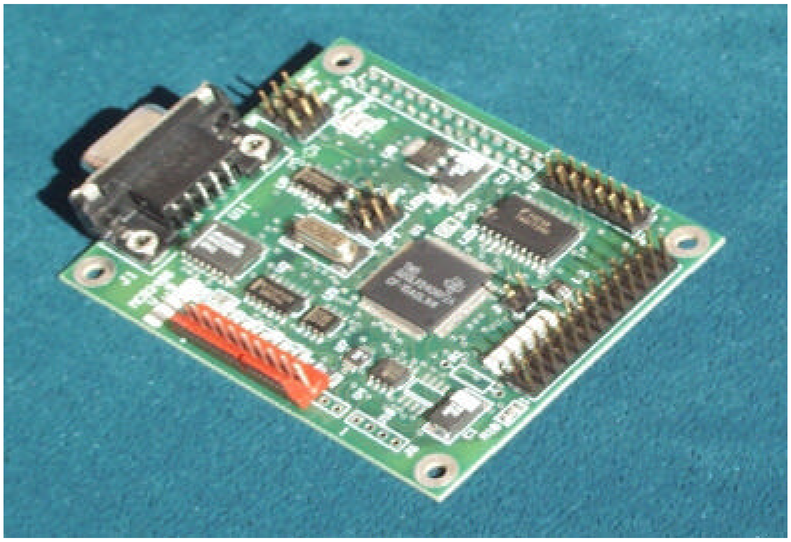


Fig. 3.1. MCB2406 Motor Control Board

By taking results from sinusoidal operation into account, we can observe the following:

1.  The efficiency of the motor driven by a synchronous regulator is always the best.  For phase current controlled, or simulated sine drives, the efficiency is a function of current-loop tuning.  This is due to phase lag of the motor current, which is related to current-loop bandwidth.  As mentioned before, this phase lag is inherently eliminated in the synchronous regulator.  With an appropriate phase advance technique, efficiency of the phase current controlled drives may reach that of the synchronous regulator.

2. Compared to sinusoidal drives, 6-step drives produce excessive torque ripple of 6 times the electrical line frequency and its harmonics. This torque ripple produces audible noise and increased system loss. Sinusoidal drives reduce torque ripple at the expense of high resolution feedback and energization of sinusoidal-like currents at all 3 phases instead of two at a time. The simulated sinusoidal operation based on the Hall sensor can be attractive in many cost-sensitive, but high performance applications.

## IV. CONCLUDING REMARKS

Although many different types of PWM motor control IC's for brushless motors are available in the market, switching schemes of these IC's are either fixed or limited in flexibility. It was demonstrated that a DSP drive could produce many different switching schemes. In this article, more than 5 different switching schemes are presented and the relative advantages and drawbacks of each mode are compared. It was found that selection of the switching scheme affects performance characteristics such as current ripple in DC link, line current harmonics, and losses in the motors and drives. Based on the motor parameters and application requirements, selection of an optimal switching scheme and PWM frequency can improve operating efficiency and motor/drive sizing. Based on load test data, efficiency and power loss were compared for each switching scheme. In addition, test results from sinusoidal operations were included in the discussion.

## REFERENCE

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# APPENDIX A:  MOTOR DRIVE TEST DATA

### 1. Motor #1  Poly-Scientific Brushless Motor BN23-28PM-01LH,  8-pole, Hall sensor only (0.266 Ohms, 253 uH)

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 12.00 | 1.576 | 14.804 | 10.00 | 2001 | 78.28 | 4.11 | 0.807 |
| pwm 4 | 12.00 | 1.585 | 14.826 | 10.02 | 2000 | 77.95 | 4.19 | 0.824 |
| pwm 3 | 12.00 | 1.608 | 14.796 | 10.00 | 2000 | 76.68 | 4.50 | 0.884 |
| pwm 2 | 12.00 | 1.615 | 14.833 | 10.02 | 2001 | 76.54 | 4.55 | 0.893 |
| pwm 1 | 12.00 | 1.658 | 14.804 | 10.00 | 2001 | 74.40 | 5.09 | 1.000 |
| pwm 0 | 12.00 | 1.607 | 14.796 | 10.00 | 2000 | 76.73 | 4.49 | 0.881 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 11.70 | 3.328 | 29.681 | 20.06 | 2000 | 76.23 | 9.26 | 0.841 |
| pwm 4 | 11.70 | 3.374 | 29.622 | 20.02 | 2000 | 75.04 | 9.85 | 0.895 |
| pwm 3 | 11.70 | 3.422 | 29.622 | 20.02 | 2000 | 73.99 | 10.42 | 0.946 |
| pwm 2 | 11.70 | 3.411 | 29.652 | 20.04 | 2000 | 74.30 | 10.26 | 0.932 |
| pwm 1 | 11.70 | 3.475 | 29.652 | 20.04 | 2000 | 72.93 | 11.01 | 1.000 |
| pwm 0 | 11.70 | 3.422 | 29.652 | 20.04 | 2000 | 74.06 | 10.39 | 0.944 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 11.40 | 5.430 | 44.448 | 30.04 | 2000 | 71.80 | 17.45 | 0.863 |
| pwm 4 | 11.40 | 5.570 | 44.477 | 30.06 | 2000 | 70.05 | 19.02 | 0.941 |
| pwm 3 | 11.40 | 5.630 | 44.507 | 30.08 | 2000 | 69.34 | 19.68 | 0.973 |
| pwm 2 | 11.50 | 5.640 | 44.684 | 30.20 | 2000 | 68.89 | 20.18 | 0.998 |
| pwm 1 | 11.40 | 5.680 | 44.537 | 30.10 | 2000 | 68.78 | 20.22 | 1.000 |
| pwm 0 | 11.50 | 5.580 | 44.389 | 30.00 | 2000 | 69.17 | 19.78 | 0.979 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 12.10 | 0.839 | 7.413 | 10.02 | 1000 | 73.02 | 2.74 | 0.592 |
| pwm 4 | 12.10 | 0.847 | 7.398 | 10.00 | 1000 | 72.19 | 2.85 | 0.616 |
| pwm 3 | 12.06 | 0.929 | 7.398 | 10.00 | 1000 | 66.03 | 3.81 | 0.823 |
| pwm 2 | 12.10 | 0.918 | 7.413 | 10.02 | 1000 | 66.74 | 3.69 | 0.799 |
| pwm 1 | 12.06 | 0.997 | 7.398 | 10.00 | 1000 | 61.53 | 4.63 | 1.000 |
| pwm 0 | 12.10 | 0.929 | 7.413 | 10.02 | 1000 | 65.95 | 3.83 | 0.828 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 11.90 | 1.891 | 14.870 | 20.10 | 1000 | 66.08 | 7.63 | 0.706 |
| pwm 4 | 11.90 | 1.933 | 14.811 | 20.02 | 1000 | 64.39 | 8.19 | 0.758 |
| pwm 3 | 11.89 | 2.066 | 14.796 | 20.00 | 1000 | 60.26 | 9.76 | 0.903 |
| pwm 2 | 11.90 | 2.037 | 14.811 | 20.02 | 1000 | 61.10 | 9.43 | 0.872 |
| pwm 1 | 11.88 | 2.156 | 14.796 | 20.00 | 1000 | 57.79 | 10.81 | 1.000 |
| pwm 0 | 11.90 | 2.068 | 14.811 | 20.02 | 1000 | 60.18 | 9.80 | 0.907 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| SimulSine | 11.69 | 3.273 | 22.416 | 30.30 | 1000 | 58.58 | 15.85 | 0.786 |
| pwm 4 | 11.68 | 3.347 | 22.194 | 30.00 | 1000 | 56.77 | 16.90 | 0.838 |
| pwm 3 | 11.65 | 3.517 | 22.194 | 30.00 | 1000 | 54.16 | 18.79 | 0.931 |
| pwm 2 | 11.66 | 3.480 | 22.194 | 30.00 | 1000 | 54.70 | 18.38 | 0.911 |
| pwm 1 | 11.64 | 3.640 | 22.194 | 30.00 | 1000 | 52.38 | 20.18 | 1.000 |
| pwm 0 | 11.66 | 3.500 | 22.194 | 30.00 | 1000 | 54.38 | 18.62 | 0.923 |

**2. Motor #2, Brushless motor SKC LA052-040, 4-pole, Hall sensor & Encoder feedback (1.18 Ohms, 4.4 mH)**

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| Sin SR | 18.45 | 1.040 | 14.848 | 10.01 | 2005 | 77.40 | 4.33 | 0.860 |
| Sin PhR | 18.44 | 1.070 | 14.848 | 10.01 | 2005 | 75.24 | 4.88 | 0.969 |
| pwm 4 | 18.43 | 1.150 | 14.811 | 10.00 | 2002 | 69.88 | 6.38 | 1.266 |
| pwm 3 | 18.43 | 1.163 | 14.811 | 10.00 | 2002 | 69.10 | 6.62 | 1.314 |
| pwm 2 | 18.44 | 1.080 | 14.811 | 10.00 | 2002 | 74.37 | 5.10 | 1.012 |
| pwm 1 | 18.44 | 1.075 | 14.781 | 9.98 | 2002 | 74.57 | 5.04 | 1.000 |
| pwm 0 | 18.44 | 1.070 | 14.774 | 9.98 | 2001 | 74.88 | 4.96 | 0.983 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| Sin SR | 18.30 | 2.394 | 29.726 | 20.04 | 2005 | 67.84 | 14.09 | 0.978 |
| Sin PhR | 18.30 | 2.397 | 29.815 | 20.10 | 2005 | 67.96 | 14.06 | 0.976 |
| pwm 4 | 18.30 | 2.459 | 29.637 | 20.02 | 2001 | 65.87 | 15.35 | 1.066 |
| pwm 3 | 18.29 | 2.473 | 29.637 | 20.02 | 2001 | 65.51 | 15.60 | 1.083 |
| pwm 2 | 18.30 | 2.404 | 29.637 | 20.02 | 2001 | 67.36 | 14.36 | 0.997 |
| pwm 1 | 18.30 | 2.406 | 29.627 | 20.02 | 2001 | 67.28 | 14.41 | 1.000 |
| pwm 0 | 18.30 | 2.430 | 29.622 | 20.00 | 2002 | 66.62 | 14.84 | 1.030 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| Sin SR | 18.49 | 0.590 | 7.405 | 10.00 | 1001 | 67.88 | 3.50 | 0.757 |
| Sin PhR | 18.49 | 0.599 | 7.398 | 9.99 | 1001 | 66.80 | 3.68 | 0.794 |
| pwm 4 | 18.49 | 0.703 | 7.398 | 10.00 | 1000 | 56.92 | 5.60 | 1.209 |
| pwm 3 | 18.48 | 0.725 | 7.405 | 10.00 | 1001 | 55.29 | 5.99 | 1.293 |
| pwm 2 | 18.49 | 0.630 | 7.405 | 10.00 | 1001 | 63.59 | 4.24 | 0.916 |
| pwm 1 | 18.48 | 0.650 | 7.383 | 9.98 | 1000 | 61.45 | 4.63 | 1.000 |
| pwm 0 | 18.48 | 0.641 | 7.398 | 10.00 | 1000 | 62.44 | 4.45 | 0.961 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| Sin SR | 18.40 | 1.500 | 14.818 | 20.01 | 1001 | 53.70 | 12.78 | 0.921 |
| Sin PhR | 18.39 | 1.533 | 14.811 | 20.00 | 1001 | 52.52 | 13.39 | 0.965 |
| pwm 4 | 18.39 | 1.610 | 14.826 | 20.02 | 1001 | 50.09 | 14.77 | 1.065 |
| pwm 3 | 18.38 | 1.676 | 14.826 | 20.02 | 1001 | 48.14 | 15.97 | 1.151 |
| pwm 2 | 18.40 | 1.523 | 14.826 | 20.02 | 1001 | 52.92 | 13.19 | 0.950 |
| pwm 1 | 18.39 | 1.560 | 14.811 | 20.02 | 1000 | 51.63 | 13.88 | 1.000 |
| pwm 0 | 18.39 | 1.538 | 14.826 | 20.02 | 1001 | 52.41 | 13.46 | 0.970 |

### 3. Motor #3, DC Motor (2.095 Ohms, 2.240 mH), Encoder feedback.

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| pwm 4 | 30.20 | 0.973 | 18.532 | 10.02 | 2500 | 63.07 | 10.85 | 0.935 |
| pwm 3 | 30.20 | 0.982 | 18.532 | 10.02 | 2500 | 62.49 | 11.12 | 0.958 |
| pwm 2 | 30.20 | 0.986 | 18.532 | 10.02 | 2500 | 62.24 | 11.24 | 0.969 |
| pwm 1 | 30.20 | 0.998 | 18.532 | 10.02 | 2500 | 61.49 | 11.61 | 1.000 |
| pwm 0 | 30.20 | 0.980 | 18.532 | 10.02 | 2500 | 62.62 | 11.06 | 0.953 |

| Drive Type | Input Vtg | Input C'rt | Output | Torque | Speed | Overall Eff. | Total Loss | Ratio of Loss |
|---|---|---|---|---|---|---|---|---|
| | (V) | (Arms) | (W) | (oz-in) | (RPM) | (%) | (W) | (pwm1 = 1) |
| pwm 4 | 30.10 | 1.933 | 37.1978 | 20.08 | 2504 | 63.93 | 20.99 | 0.975 |
| pwm 3 | 30.10 | 1.943 | 37.1978 | 20.08 | 2504 | 63.60 | 21.29 | 0.989 |
| pwm 2 | 30.10 | 1.943 | 37.1978 | 20.08 | 2504 | 63.60 | 21.29 | 0.989 |
| pwm 1 | 30.10 | 1.953 | 37.2719 | 20.12 | 2504 | 63.40 | 21.51 | 1.000 |
| pwm 0 | 30.10 | 1.930 | 37.1978 | 20.08 | 2504 | 64.03 | 20.90 | 0.971 |

Notes: SimulSine: Simulated sinusoidal mode based on Hall sensor feedback.

Sin SR: Sinusoidal mode with Synchronous regulator current control (Encoder feedback)

Sin PhR: Sinusoidal mode with Phase current regulator (Encoder feedback)