Trapezoidal Commutation for Brushless DC Motors

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Introduction

Brushless DC Motors (BLDC) have been widely used in the industry by demand for increased functionality, precision, increased energy efficiency, and better utilization of primary energy sources. Due to the large torque to volume ratio, high reliability, small size, low cost, and high efficiency, BLDC is a most suitable choice for electric motor application. There are two major commutation techniques: trapezoidal commutation and sinusoidal commutation. The back EMF and rotor-position sensing for the two commutations are different. The back EMF is trapezoidal and a low-resolution shaft-position sensor is used to synchronize the switching of the drive transistors with the rotor position, substantial field weakening is not required for trapezoidal commutation; the back EMF is sinusoidal, and encoder or resolver is used to get rotor position for sinusoidal commutation.

In this application note, a BLDC motor application that has been built using discrete components. The key functional blocks comprise a battery, digital control, drivers, and a three-phase inverter as shown in Figure 1.

The power loss breakdown of a single-phase is analyzed based on the AON6500 evaluation board, which give a good guidance of trapezoidal commutation brushless DC motors power losses distribution.

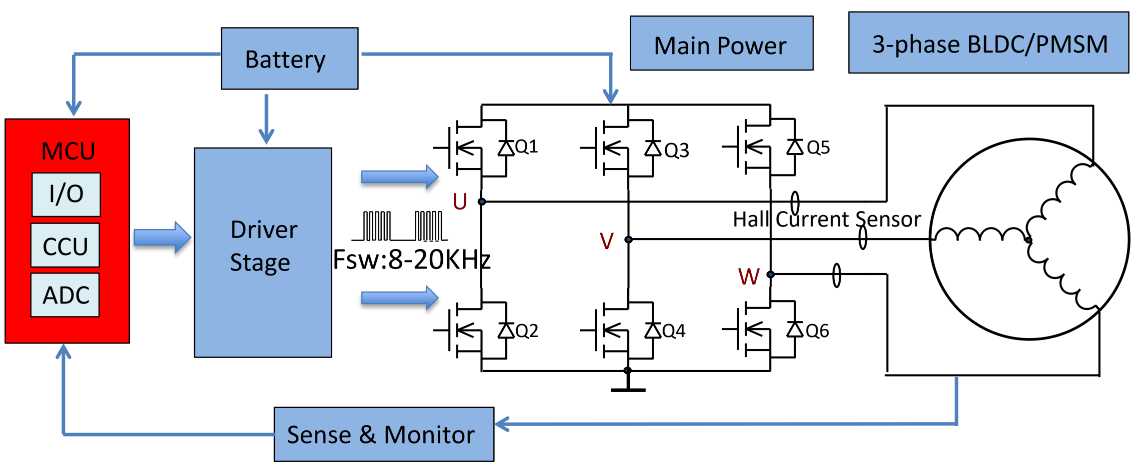


Figure 1. The Block Diagram Brushless DC Motors Control Applying to Power Tool

Block (Trapezoidal) Commutation

There are six distinctive modes of operation in a block commutation scheme. Table 1 provides the sequence of active power devices during a specific block, while Figure 2 shows the exact commutation waveforms of a three-phase inverter that is used to control a power tool BLDC motor.

Table 1. Active Power Devices in a Block Commutation Scheme

Commutation table				
BLOCK	HS MOSFET	LS MOSFET	Sync MOSFET	Hall Pattern
I	Q1	Q4	Q2	101
II	Q1	Q6	Q2	100
III	Q3	Q6	Q4	110
IV	Q3	Q2	Q4	010
V	Q5	Q2	Q6	011
VI	Q5	Q4	Q6	001

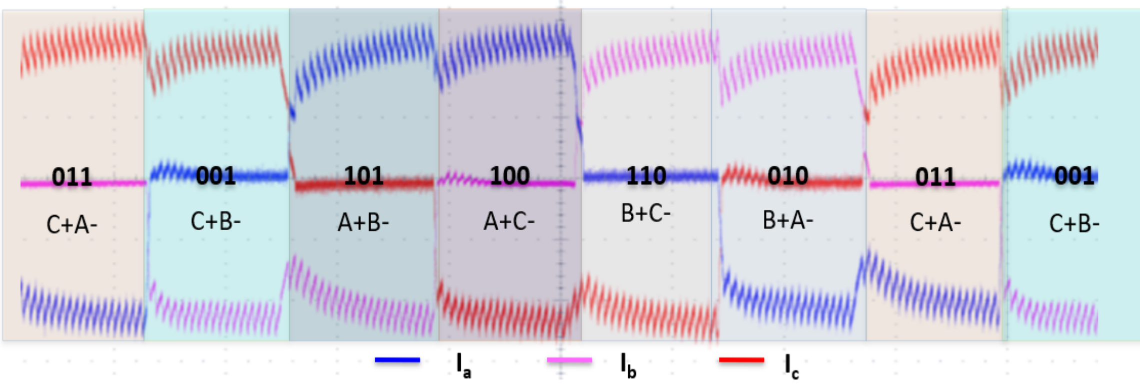


Figure 2. Commutation Waveforms of a 3-Phase Inverter

Back-EMF Vs Speed

A magnetic field rotating through a coil that is conducting will produce the electromotive force, which is called back electromotive force (Back-EMF) E. The faster the motor speed, the larger the back-EMF will be because a greater amount of magnetic flux from the magnet passed through the coil's magnetic flux per unit period. A simplified model of a BLDC motor running at the steady-state is shown in Figure 3. The winding inductance effect can be ignored at steady state, the rotor is replaced by a bar, and the B_{total} is used to represent the total magnetic flux density between the stator and rotor. F_{ind} is the motor force and the F_{load} is the load force. When the BLDC motor reaches a steady- state, the constant velocity can be obtained:

$$v = \frac{E}{B_{total}L} = \frac{DV_{battery} - iR_{winding}}{B_{total}L} \qquad (1)$$

where L is rotor length. For trapezoidal commutation brushless DC motors, the phase voltage V_P is controlled by switching the duty cycle D.

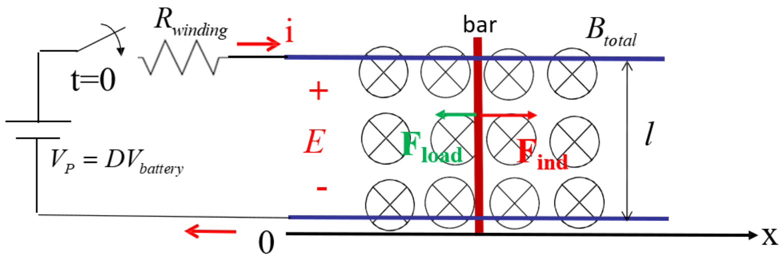


Figure 3. The Simplified Model of a BLDC Motor

According to the simplified model of a BLDC motor, when the supply voltage to a BLDC motor increases, the faster the motor rotates, but the voltage across the winding resistance increases, causing the rotation current to increase, which will increase the motor torque. The rotational speed increases until an increase in back-EMF caused by the increase in rotational speed and the current flowing in the motor settles into a new stable state. When the BLDC motor supply voltage keeps constant, the motor load keeps increase. The BLDC motor slows down as the load increase. As a result, the back-EMF will decrease, and the current flowing the winding and the output torque will also increase at the same time.

Neutral-point of BLDC Motor Windings

As shown in Figure 4 (a), the Phase-A and Phase-B windings are short-circuited to Vin and GND respectively. Hence, V_a=Vin and V_b=0. Let the current that flows from Vin to GND via the phase-A and phase-B windings. At this time, the neutral-point voltage is at the midpoint of (Vin- Ea) and (0-Eb) because the voltage drops across Phase-A and Phase-B are equal:

$$V_N = \frac{(V_{in} - Ea - Eb)}{2} \qquad (2)$$

Equation 1 can also be derived from the fact that the neutral-point voltage is lower than the neutral-point reference voltage Vin/2 by (Ea+Eb)/2. The three-phase back-EMF is balanced and can be calculated as:

$$E_a + E_b = -E_c \qquad (3)$$

Putting the equation 2 to equation 1, V_N can be simplified as:

$$V_N = \frac{V_{in} + E_c}{2} \qquad (4)$$

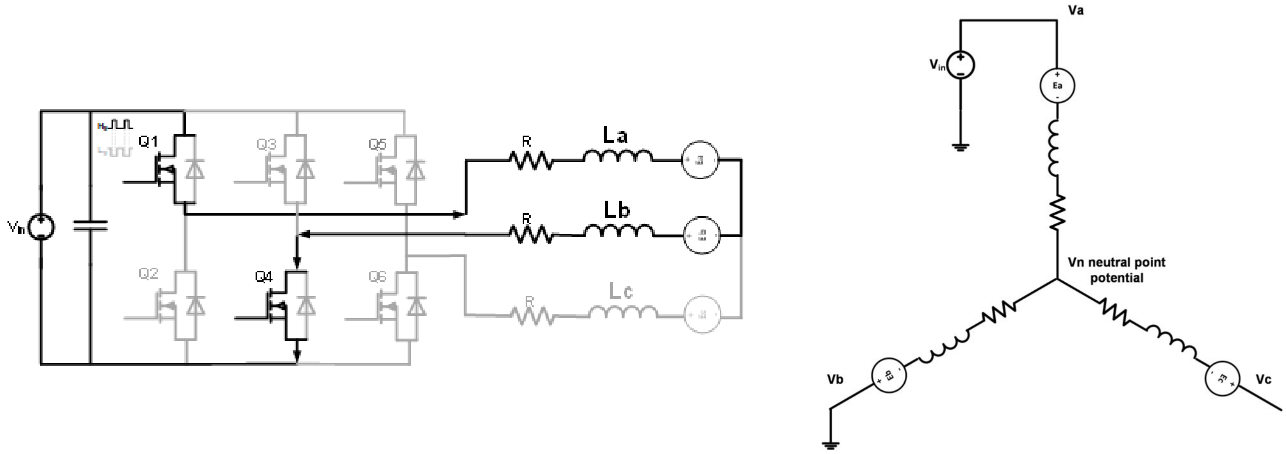
From the circuit, it can be obtained that $V_c = V_N + E_C$, substituting the Equation 3 into it, Vc can be expressed as:

$$V_c = \frac{V_{in}}{2} + \frac{3}{2}E_c = \frac{V_a + V_b}{2} + \frac{3}{2}E_c \qquad (5)$$

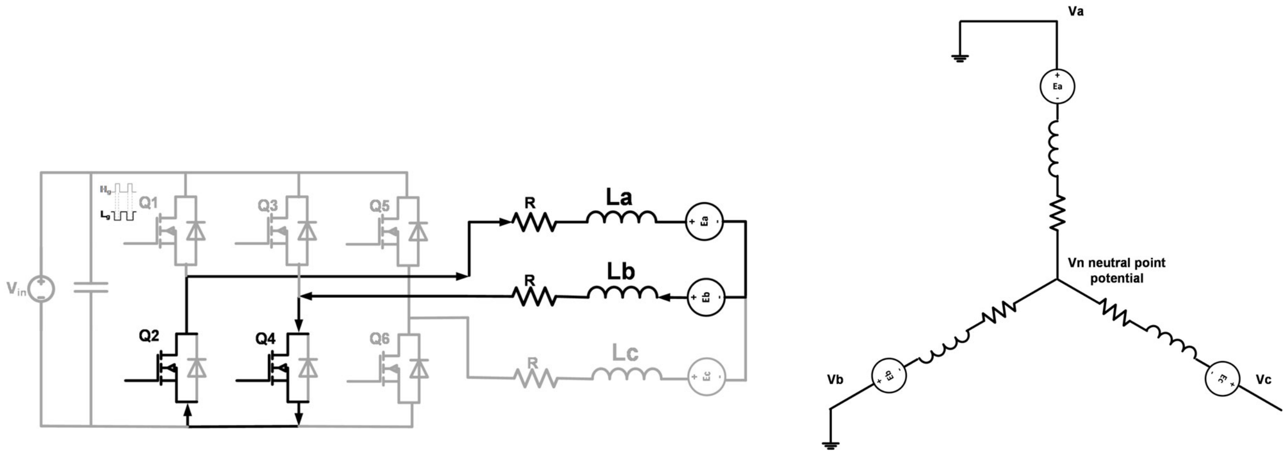
Figure 4 (B) shows the Q1 is off, Q2 is on, so the Vin= 0, then

The Commutation waveform during this period can be measured and the approximate Vc curve can be plotted. Finally, back-EMF can be approximately obtained as shown in Figure 5.

$$V_c = \frac{3}{2} E_c \qquad (6)$$



(a) Q1 and Q4 is on



(b) Q2 and Q4 is on

Figure 4. Inverter Circuit and Neutral-point Voltage and Voltage of Each Phase

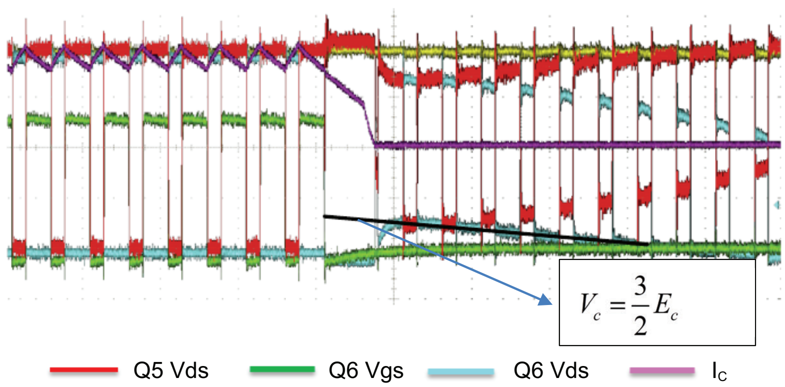
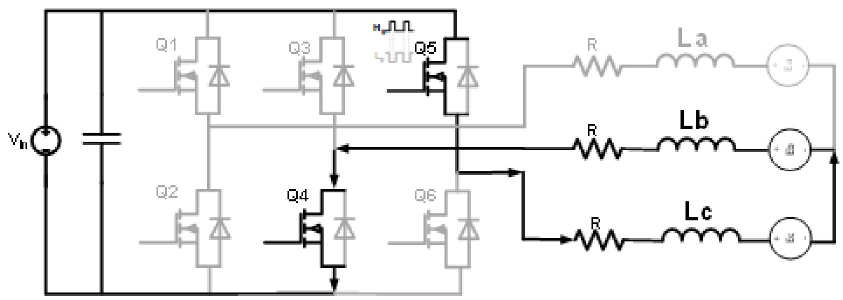


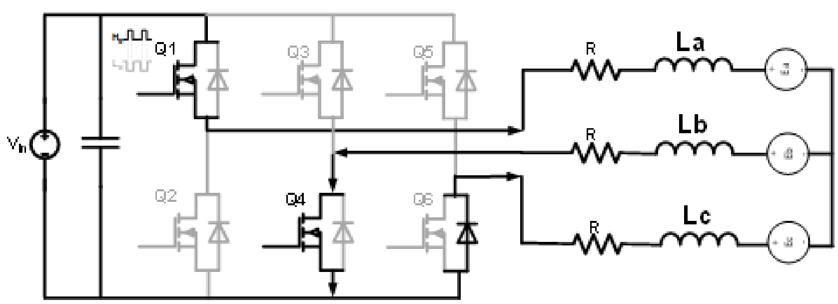
Figure 5. Commutation Wave during Q1 is off, Q2 and Q4 is on

Commutation Periods

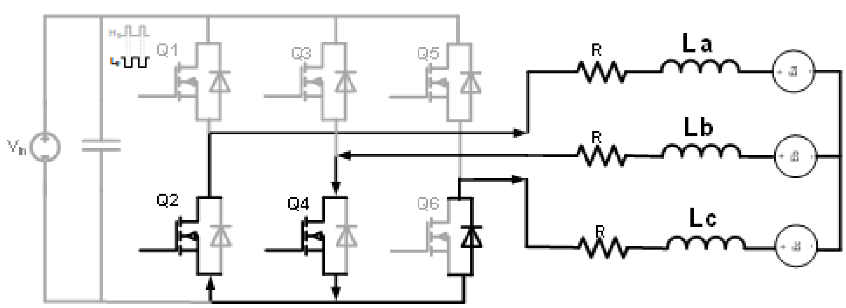
Figure 6 shows the commutation switching waveform from phase CB to Phase AB. Phase C and Phase B are conducting as shown in Figure 6 (a). During the commutation from phase CB to phase AB, the Q5 remains off after being on for 120 electrical degrees. After the Q5 off, a current flow back through the body diode (during the dead time) and Q6 until the energy stored in the Phase C winding disappears. Since the cathode of the body diode and Q6 is connected to GND, its anode voltage decrease to the GND voltage while the freewheel current continues flowing. After that, the voltage at the Phase C terminal becomes equal to the back-EMF voltage.



(a) Q4 and Q5 is on



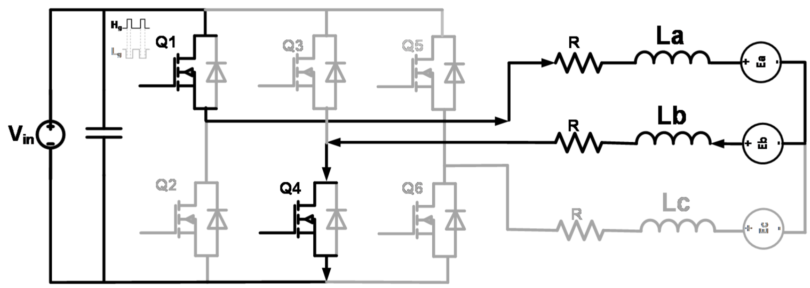
(b) Q1, Q4 and D6 is on



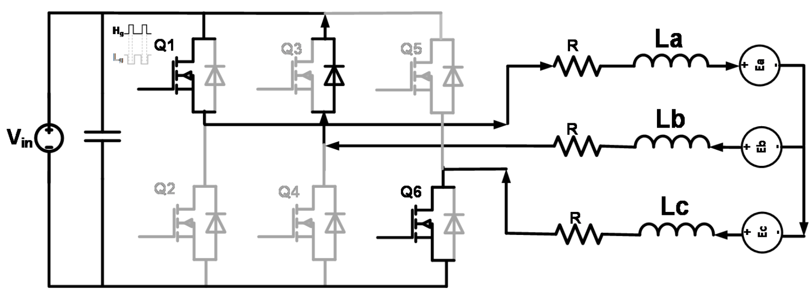
(c) Q2, Q4 and D6 is on

Figure 6. Switching Waveform from Phase CB to AB

Figure 7 shows the commutation switching waveform from phase AB to Phase AC. Phase A and Phase B are conducting as shown in Figure 7 (a). During the commutation from phase AB to phase AC, the Q4 remains off after being on for 120 electrical degrees. After the Q4 off, a current flows back through the body until the energy stored in the Phase B winding disappears. Since the cathode of the body diode is connected to V_{in}, its anode voltage decrease to the V_{in} voltage while the freewheel current continues flowing. After that, the voltage at the Phase B terminal becomes equal to the back-EMF voltage.



(a) Q1 and Q4 is on



(b) Q1, Q6 and D3 is on

Figure 7. Switching Waveform from Phase AB to AC

Testing System Set Up

Table 2 shows the detail information of testing system and Figure 8 shows the BLDC testing set up in detail.

Table 2. Testing System Information

Testing System Information	
BLDC Board	AON6500 EVB
BLDC Motor	4 Poles BLDC
Coupling	1/2" x 11mm
Dynamometer	MAGTROL HD-715-6N-5160
	Maximum Power 3300W

BLDC Board Motor Coupling Dynamometer

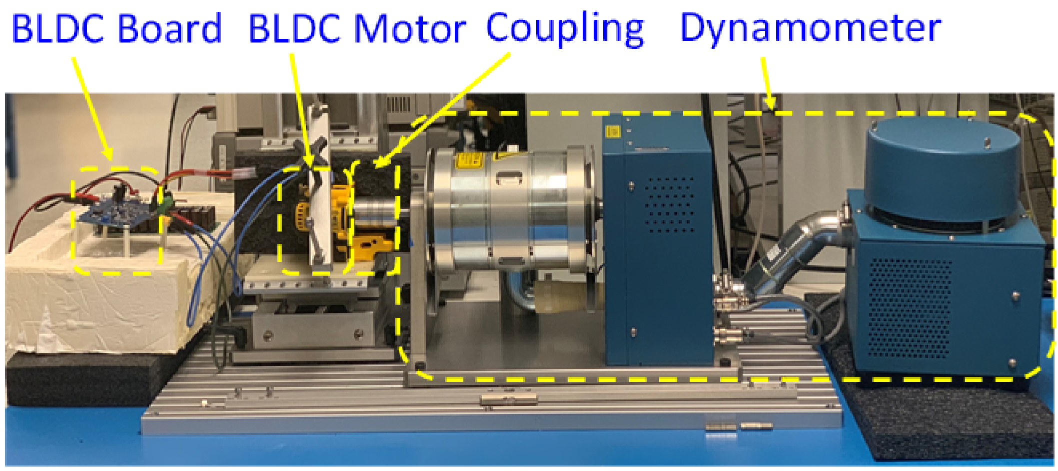


Figure 8. The BLDC Motor Testing Set-Up

Power Loss Distribution

The power loss distribution is based on the AON6500 MOSFET evaluation board as shown in Figure 9. Table 3 shows the MOSFET AON6500 the parameters in detail.

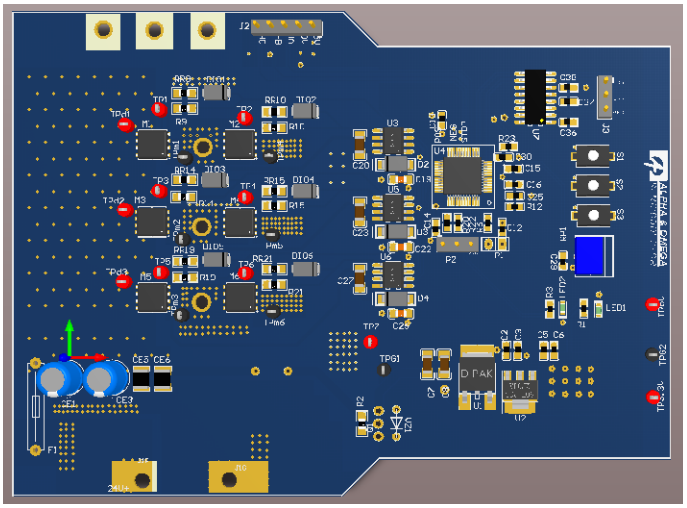
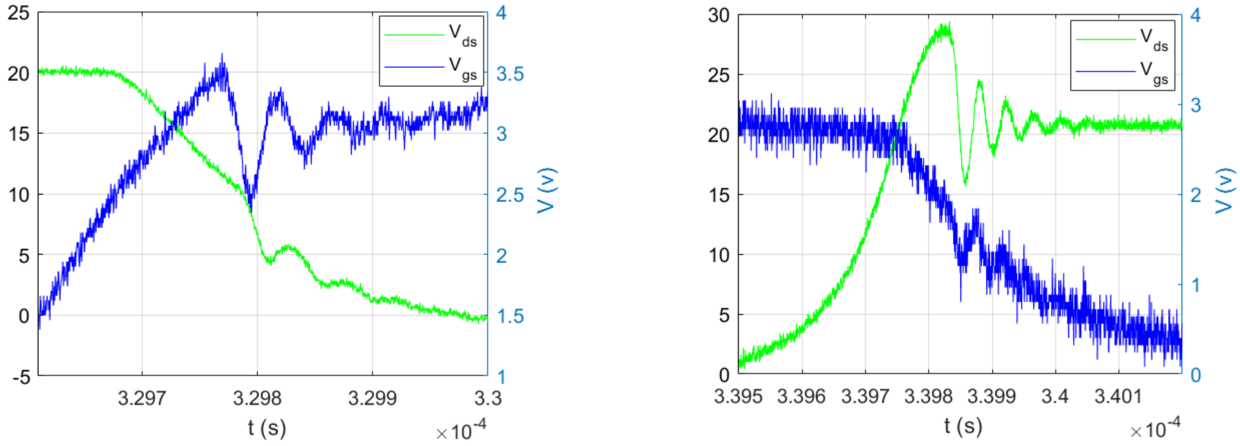


Figure 9. The BLDC Evaluation Board

Table 3. MOSFET AON6500 Parameters

Part Number	Application	BV_{DS} (V)	$R_{DS(ON)}$ (mΩ) typ at V_{GS} =		V_{GS}(th) (V)	Coss @ 20V (pF)	Ciss @ 20V (pF)	Crss @ 20V (pF)	R_G (ohms)
			10V	4.5V					
AON6500	HS/LS	30	<0.95	<1.3	1.4	1850	7310	35	1.1

Figure 10 shows the MOSFET AONS34356 turns on and off waveform. MOSFET switching frequency is 20 kHz. The turn-on time is around 300 ns and the turn-off time is around 350 ns. The motor has 2 poles pairs, which means the electrical speed is twice the mechanical speed. The following power loss dissipation is based on the motor speed is 5110 rpm, and the duty cycle is 0.32.



(a) MOSFET Turn on

(b) MOSFET turn off

Figure 10. MOSFET AON6500 Turn on and off Waveform

Figure 11 shows one high side MOSFET AON6500 power dissipation. The turn-off loss is the maximum power loss, which takes 56.31% of the total power dissipation. The turn-on power loss is 27.56% of total power loss, which is the second maximum power dissipation. The third biggest dissipation is conduction loss, and it takes 12.94%. The one low side MOSFET AON6500 power dissipation is shown in Figure 12. The turn-on and turn-off loss can be neglected because the MOSFET turns on and off at nearly zero voltage. For complementary switching control, in one phase, the high-side device and low-side device keep complementary switching; in another phase, the low-side device is turned on; and in the remaining phase, both the high- and low-side devices are turned off. From the above description, the low side MOSFET conduction loss should take the maximum power dissipation. As shown in Figure 12, the low side MOSFET takes 84.8% of the total low side MOSFET power dissipation. Figure 13 shows the total power loss of one high and low side MOSFET, the high side MOSFET power dissipation is around 1.25 times bigger than the low side MOSFET power dissipation.

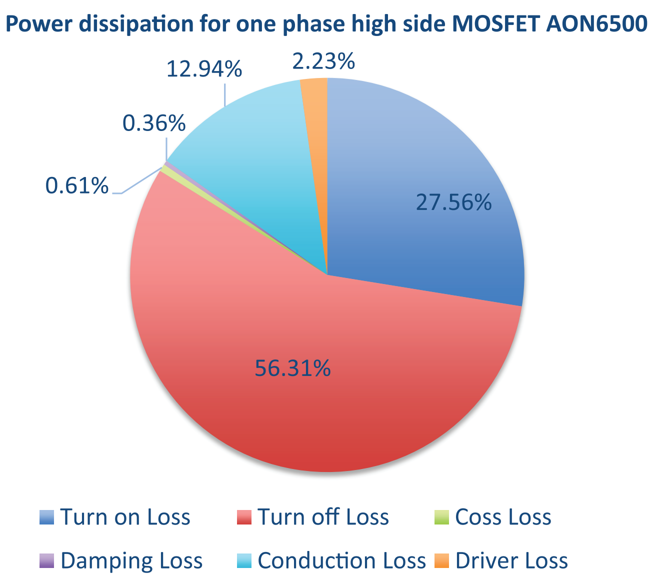


Figure 11. Power Dissipation of one Phase High-Side MOSFET

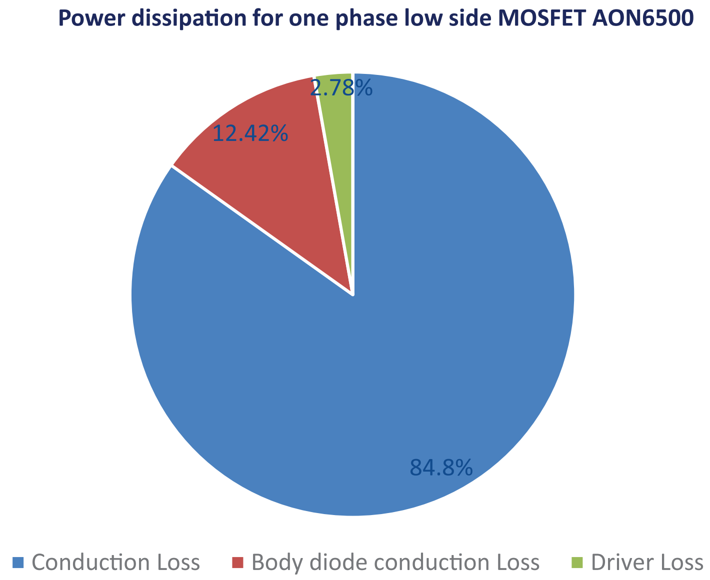


Figure 12. Power Dissipation of one Phase Low-Side MOSFET

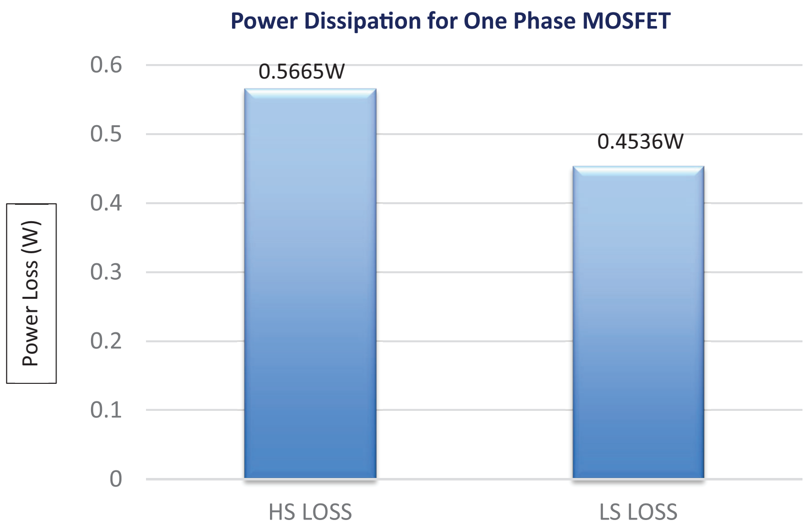


Figure 13. Total Power Loss of One High and Low Side MOSFET

Conclusion

This application describes the trapezoidal commutation and power distribution for brush-less DC motor, focusing on commutation waveforms, motor back-EMF estimation, power distribution. Alpha & Omega Semiconductor MOSFET low $R_{DS(ON)}$ AON6500 is used for the BLDC evaluation board. The turn off loss takes the maximum percentage of total high side MOSFET power loss. For the low side MOSFET power loss, the conduction loss is the biggest one.

Reference

1): He, C.; Wu, T. Permanent magnet brushless DC motor and mechanical structure design for the electric impact wrench system. Energies 2018, 11, 1360.

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