WHITE PAPER

MOTOR DRIVE IN MISSION CRITICAL SYSTEMS: PRECISION POWER ANALOG FOR BLDC MOTION CONTROL

APEX MICROTECHNOLOGY
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This white paper is an overview of BLDC motor drive and control methods. Topics include trapezoidal commutation, six-step commutation, PID controllers and PWM control principles, and includes application examples from the aerospace and defense industry. Apex provides an array of 3-phase inverters that ease the design challenges of a BLDC motor drive system.

1.0 INTRODUCTION

When comparing the attributes of a brushless motor with those of its brush motor equivalent, the most notable difference is the reduction in size and weight for the brushless motor offering the same horsepower. What is less obvious is the absence of the familiar brush-commutator arrangement that has been at the heart of single-phase DC brush motors for over a century. The lack of a brush-commutator interface means brushless motors also exhibit lower acoustic noise and are virtually maintenance free.

Adding to the appeal of the brushless motor is the widening availability of microcontrollers with the special functions (routines) necessary to control the three-phase operation of brushless motors. Equally important, and more readily available, are IC drivers that deliver power to the motor and form the interface between the microcontroller and the brushless motor itself.

Commutation refers to an on-going sequence of steps that specifies the application of voltages to the proper motor phases and imparts the desired motor rotation throughout each successive 360-degree revolution. The switching of phases is called commutation. Brush-type DC motors use electromechanical commutation that is achieved via graphite brushes that make electrical contact to a circular commutator mounted on the rotor. The motor is designed so that torque is maximized as the motor shaft rotates throughout each full 360-degree rotation. In a brushless motor commutation is usually performed by switching electronics that rely on devices such as Hall sensors. This arrangement is shown in figures 1 and 2. The Hall sensors feedback the position of the rotor at known instants to the control electronics. However, there are alternative methods employing sensorless commutation.

Brushless motors use what is commonly referred to as “inside out” commutation because their design is essentially that of a brush motor turned inside out. Although the stators in the motor are wound, the rotor is not. Instead, it employs a permanent magnet rotor. The magnetic attraction of the rotor to the revolving magnetic field is induced in the wound stator poles and develops the torque necessary to rotate the motor and drive the attached load. This scenario is shown in Figure 1.

Thanks to the Hall sensors, the control circuitry always knows the exact moment to commutate. Most brushless motor manufacturers supply motors with three Hall-effect position sensors. Each sensor delivers an alternating binary high and a binary low as the rotor turns. The three sensors are offset, as illustrated in Figure 1. Each sensor aligns with one of the fields developed by one of the wound stator poles. Note that as shown in Figure 3, two windings are always energized while one winding is not.

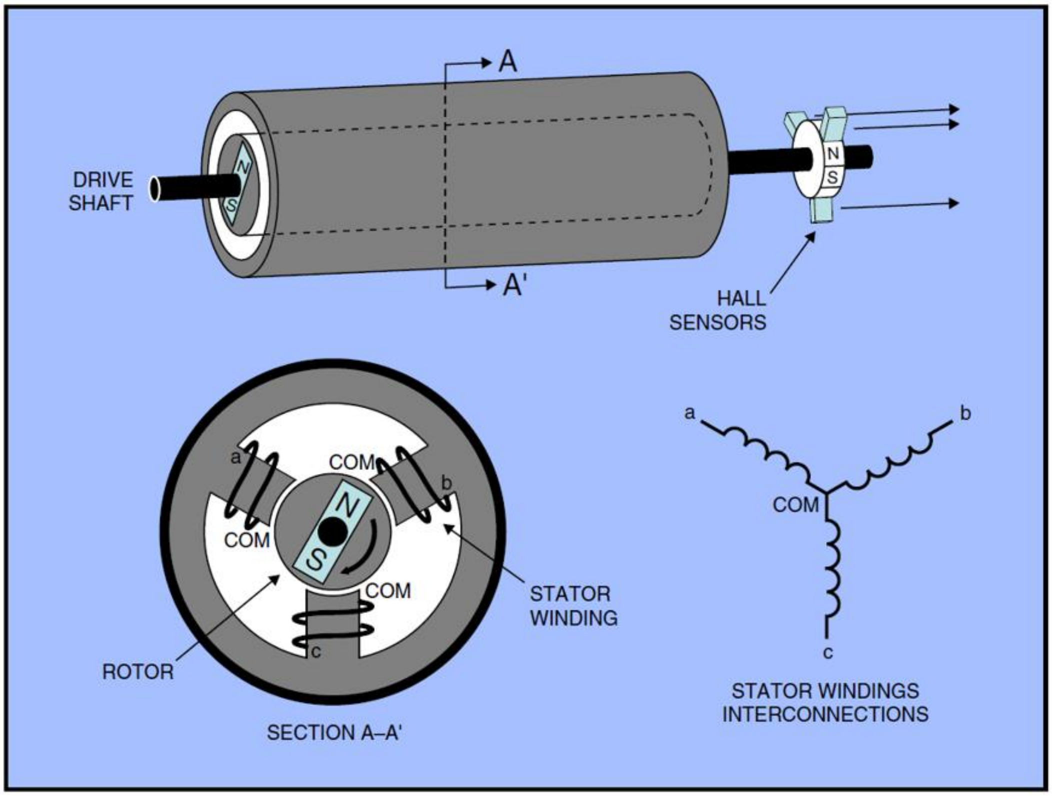


Figure 1. A Brushless Motor – A BLDC differs from a motor with brushes in that commutation is provided by sensors rather than the familiar bush-commutator arrangement found in a conventional DC motor with brushes. Also, brushless motors are synchronous in behavior because the rotor rotates at the same frequency as the magnetic field developed by the stator windings.

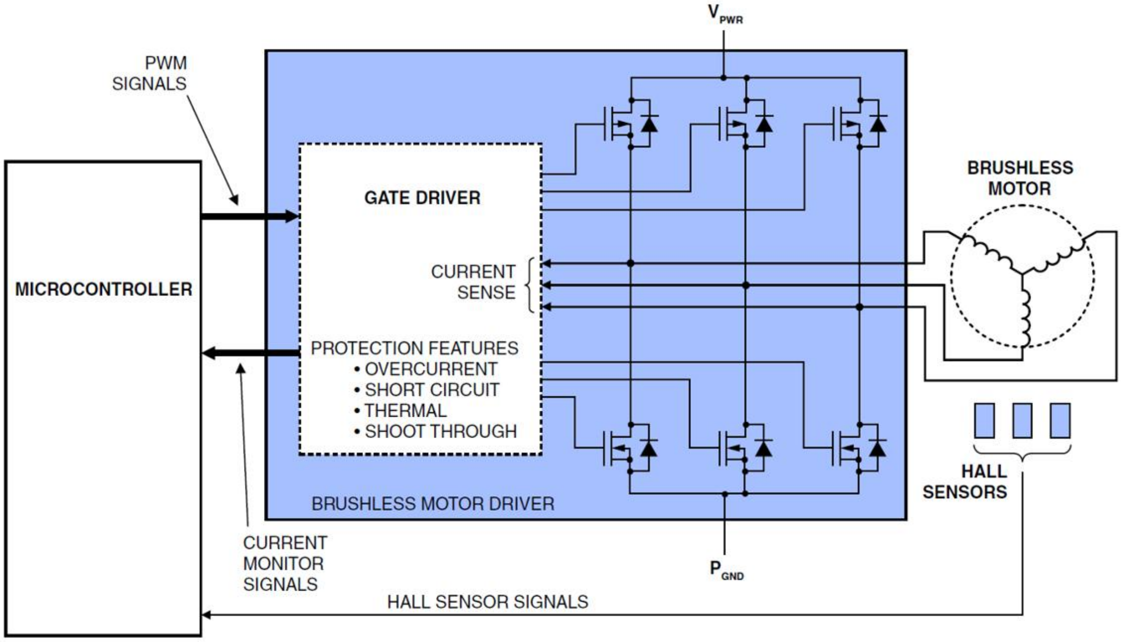


Figure 2. Block Diagram – A microcontroller and an Apex Microtechnology Brushless Motor Driver provide the necessary functions to drive a brushless motor.

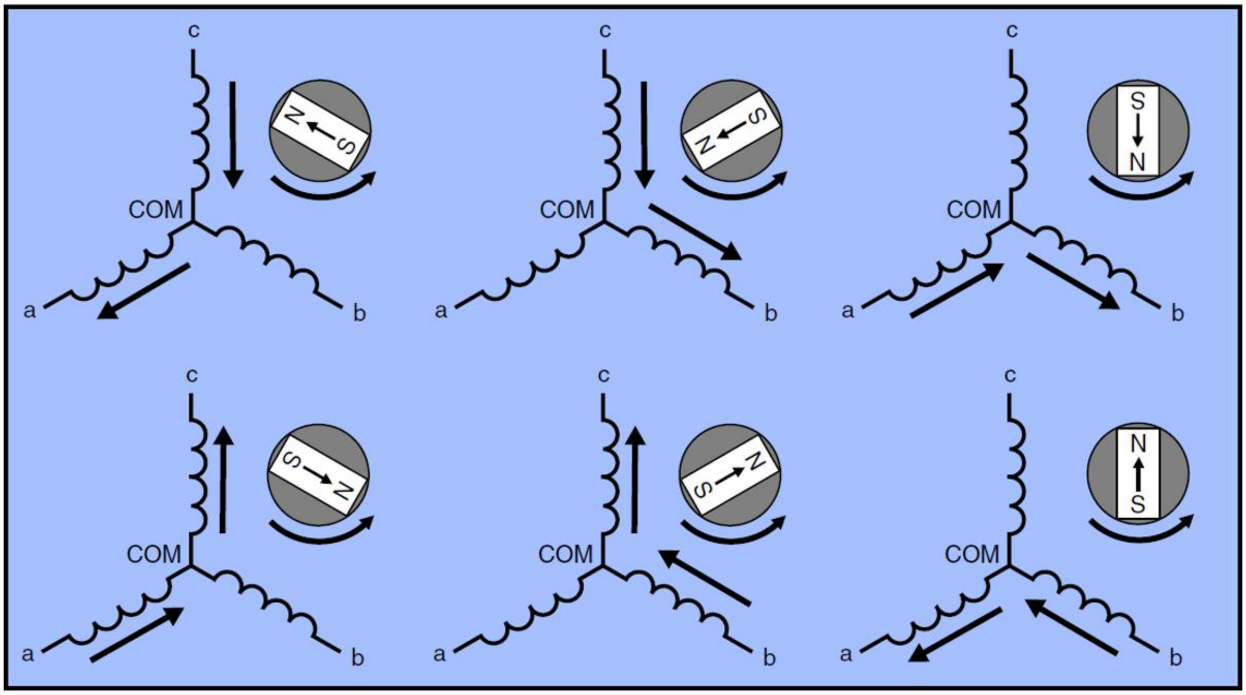
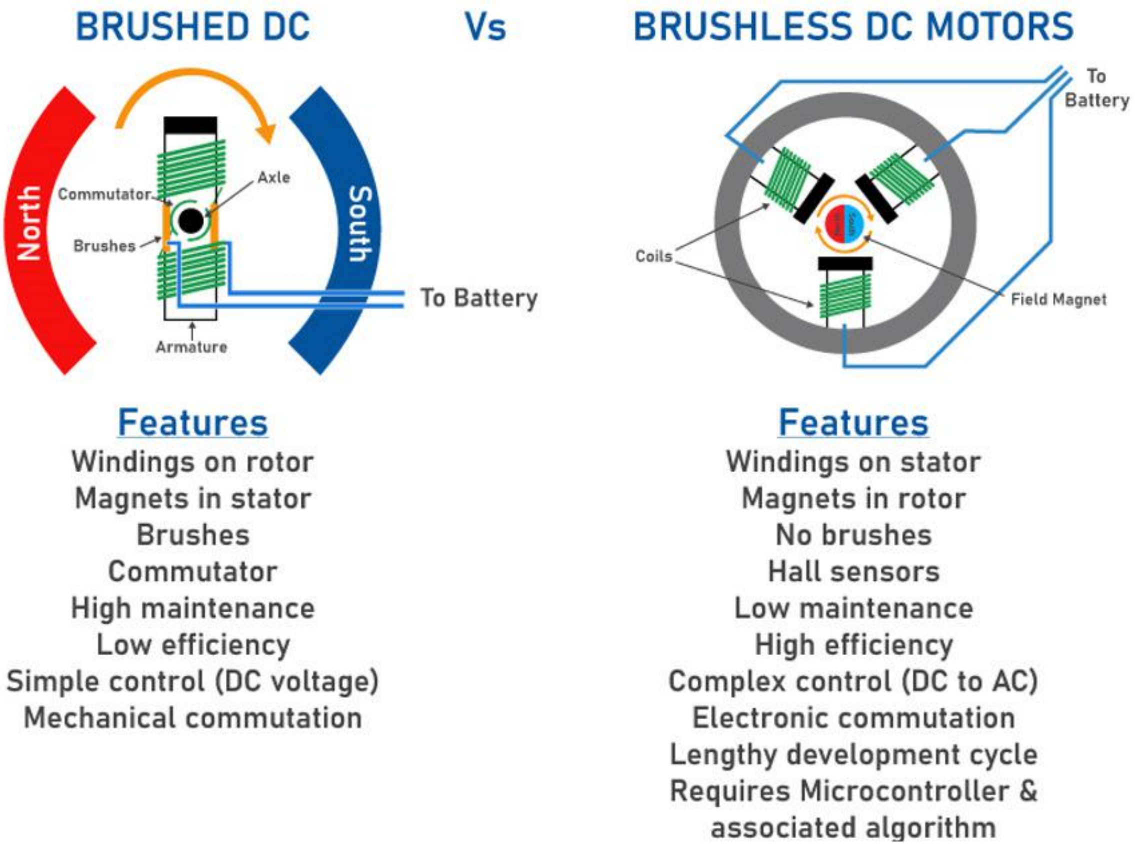


Figure 3. Six Connections – By monitoring the Hall sensors, the stator winding fields can be made to rotate so that the resultant field of the two energized stator windings and the pole of the permanent magnet rotor remain at right angles, thereby maximizing the instantaneous torque.

BLDC motors provide higher efficiency and require lower maintenance and that's why they've replaced brushed motors in many applications in the past few decades. Both types of motors operate based on a similar principle in which the rotational motion is generated through the attraction and repulsion of magnetic poles of permanent and electromagnets. However, the way these motors are controlled is very different. BLDC motors require a complex controller to convert DC power to three-phase voltages, whereas a brushed motor can be easily controlled by a DC voltage.

In brushed motors, the commutation occurs mechanically when the brushes come in contact with the commutator of the rotor as the motor is spinning. Due to this physical contact, brushes wear out over time. BLDC motors overcome the shortcomings of brushed motors by replacing mechanical commutation with electronically driven commutation.



Features
- Windings on rotor
- Magnets in stator
- Brushes
- Commutator
- High maintenance
- Low efficiency
- Simple control (DC voltage)
- Mechanical commutation

Features
- Windings on stator
- Magnets in rotor
- No brushes
- Hall sensors
- Low maintenance
- High efficiency
- Complex control (DC to AC)
- Electronic commutation
- Lengthy development cycle
- Requires Microcontroller & associated algorithm

Figure 4. Brushed DC Vs. Brushless DC Motors

2.0 TRAPEZOIDAL COMMUTATION

Trapezoidal commutation is typically used for motors that are wound deliberately to produce trapezoid shaped Back-EMF waveforms. In many cases, manufacturing tolerances cause the Back-EMF to appear distorted from a perfect trapezoid, as shown in figure 5. For the purposes of commutation and modeling, we can assume that this is close enough to a perfect trapezoidal waveform. Trapezoidal Back-EMF shape is very common for Brushless-DC (BLDC) motors, as it makes the commutation control scheme easier to understand and implement.

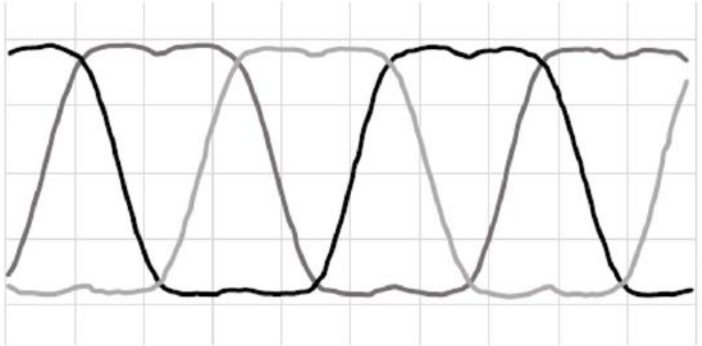
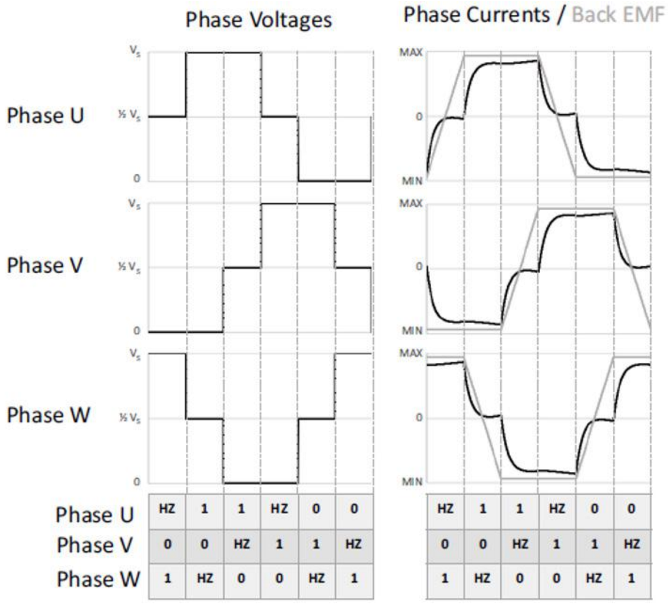


Figure 5. Trapezoidal Back-EMF waveforms

The three-phase driver or inverter control the direction of current in the stator windings. In trapezoidal commutation, there is always at least one leg in high-impedance mode. The other two inverter outputs are controlling the direction of current, with one output going to high-voltage and one output going to ground. A typical sequence of trapezoid commutation is shown in figure 6:



Phase U	HZ	1	1	HZ	0	0
Phase V	0	0	HZ	1	1	HZ
Phase W	1	HZ	0	0	HZ	1

HZ	1	1	HZ	0	0
0	0	HZ	1	1	HZ
1	HZ	0	0	HZ	1

Figure 6. Trapezoidal Commutation Sequencing. X-axes are arbitrary time scales.

Figure 6 shows a typical sequencing for a trapezoidal commutation. The charts at the bottom of the figure represent the commanded output state during each sequence: HZ (High-Impedance; both switches open), 1 (High-side switch closed, Low-side switch open), and 0 (High-side switch open, Low-side switch closed). Dead-time is not required for trapezoidal commutation, as there are no direct transitions from high voltage to ground nor from ground to high-voltage. Reversing the order shown in figure 6 will turn the motor in the opposite direction.

Amplitude control (throttling) can be achieved by super-imposing a PWM enable signal. The duty cycle of this enable signal will correspond to the amplitude, with 0% duty cycle giving no current, and 100% duty cycle giving maximum current. Most power modules, like Apex's SA310 SA110, and SA111 will have an enable input to easily control this function. If not, enable/disable can be easily implemented by commanding all 6 switches to an "open" condition (high impedance). An amplitude-controlled application might look like figure 7:

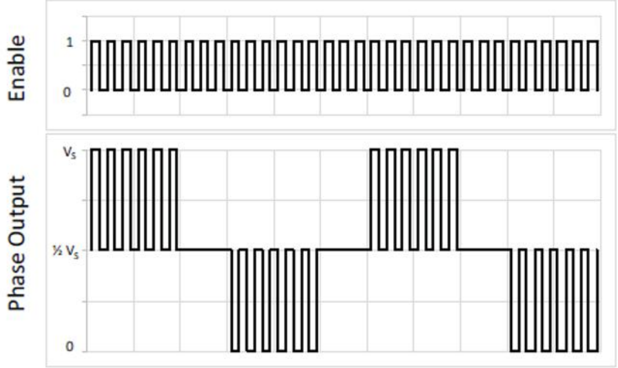
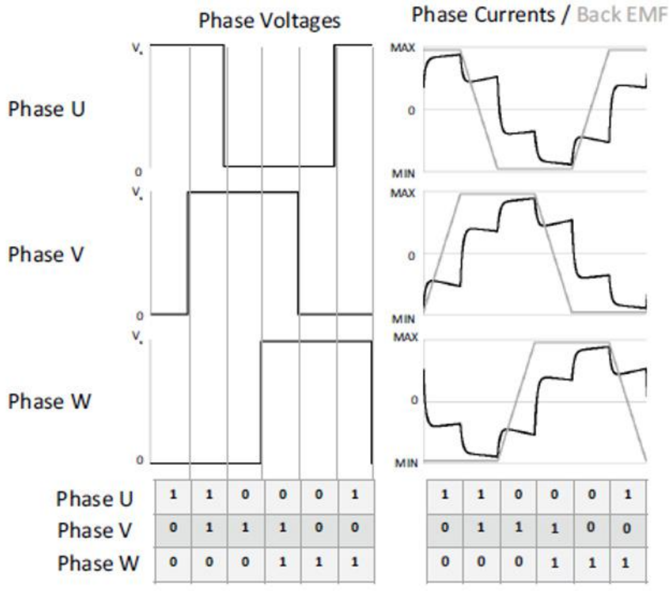


Figure 7. Trapezoidal Commutation with amplitude control

Trapezoidal commutation pairs well with motors that employ hall-effect sensors as the position feedback component. If hall sensors are not desired, similar position feedback can be achieved by sensing the Back EMF voltage of the floating leg during its high-impedance period.

3.0 SIX-STEP COMMUTATION

In contrast to trapezoidal commutation, six-step commutation closes 3 switches at once, rather than just 2. See figure 8 below:



Phase U	1	1	0	0	0	1
Phase V	0	1	1	1	0	0
Phase W	0	0	0	1	1	1

1	1	0	0	0	1
0	1	1	1	0	0
0	0	0	1	1	1

Figure 8. Six-Step Commutation Sequencing. X-axes are arbitrary time scales.

Similar to figure 6, figure 8 shows the six-step sequencing charts at the bottom for commanded output states on each phase. A "1" indicates that the output is programmed to high-voltage (high-side switch closed, low-side switch open), and a "0" indicates that the output is programmed to ground (high-side switch open, low-side switch closed). A particular "step" can be named with these symbols; for example, the left-most step would be named "100". Since this commutation method includes transitions from high-voltage to ground and vice-versa, dead-time must be considered. Reversing the above sequence reverses the motor direction.

In this commutation method, current can flow in the inverter in 1 of 2 ways: out of 1 high-side switch and into 2 low-side switches (sequences 100, 010, and 001), or out of 2 high-side switches and into 1 low-side switch (sequences 110, 011, and 101). When current is shared between 2 high-side switches or 2 low-side switches, they each carry roughly half the peak current magnitude. There are then 4 "levels" that the phase currents can be: full negative, half negative, half positive, or full positive.

Once again, amplitude control can be achieved in six-step commutation by applying a PWM enable signal similar to figure 9. All three phases should be in a high-impedance state (all switches open) during the PWM "low" times, and the phases would resume their normal sequencing during the PWM "high" times. The enable signal must be synchronous on all 3 channels for proper operation.

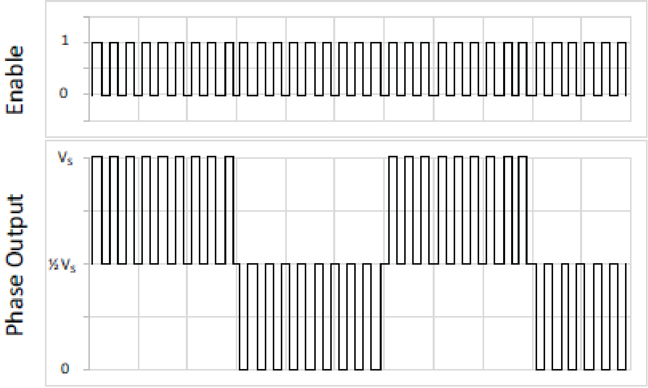


Figure 9. Six-Step Commutation with Amplitude Control

The motion of a BLDC motor is generated through six step commutation or trapezoidal control where the correct phases are energized every sixty degrees for continuous rotation of the motor.

Six-step commutation can be used for the same types of motors that Trapezoidal commutation would be used on, with some advantages and disadvantages. The advantage would be that of better torque distribution. In delta-connected motors, six-step commutation energizes 2 of the 3 legs at any one time, while trapezoidal commutation would only energize 1 leg of a delta-connected motor. This offers more area for the magnetic flux to take effect, improving the torque ripple.

The disadvantage of six-step commutation is that it does not have a floating leg for Back-EMF measurement. Position feedback must be supplied by some other form of rotor measurement, like hall-effect sensors or an encoder. Sensing phase current in six-step can be a good substitute for position feedback; Apex devices like the SA310 are particularly well-suited for this method because they provide an easy way to sense phase current.

4.0 PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER (PID)

A Proportional-integral-derivative controller (PID controller) is a feedback loop technique employed in control systems. It can be thought of as an extreme form of a phase lead-lag compensator. It is used to compare a measured value with a reference value. As employed in motor control the values may be either speed or torque. The difference value is then employed to calculate a new value to restore the value – be it speed or torque to the setpoint value. A PID loop produces accurate, stable control in cases, whereas a simple proportional control would be likely to induce a steady-state error or would induce oscillation.

Unlike more complicated control algorithms based on optimal control theory, PID controllers do not require advanced mathematics to develop a design.

A standard PID controller is also known as a "three-term" controller and can be expressed in the "parallel form" by Equation (1) or the "ideal form" by Equation (2):

$$G(s) = K_P + K_I \frac{1}{s} + K_D s \tag{1}$$

$$= K_P \left(1 + \frac{1}{T_I s} + T_D s\right) \tag{2}$$

Where:

KP is the proportional gain
KI the integral gain
KD the derivative gain
TI the integral time constant
TD the derivative time constant

- The proportional term provides an overall control response that is proportional to the error signal through the all-pass gain factor.
- The integral term reduces steady-state errors through low-frequency compensation by an integrator
- The derivative term improves the transient response through high-frequency compensation by a differentiator.

The effects of each of these three terms on closed-loop performance are summarized in Table 1.

The diagram of figure 10 represents a typical control system used for operating a BLDC motor. The input DC voltage source is proportional to the desired angular speed and provides an effective DC voltage to the three-phase inverter. The inverter converts the DC voltage to three-phase currents which activate different coil pairs. When the DC voltage is constant, the motor speed is constant. The effective DC voltage may be a filtered version of a PWM signal.

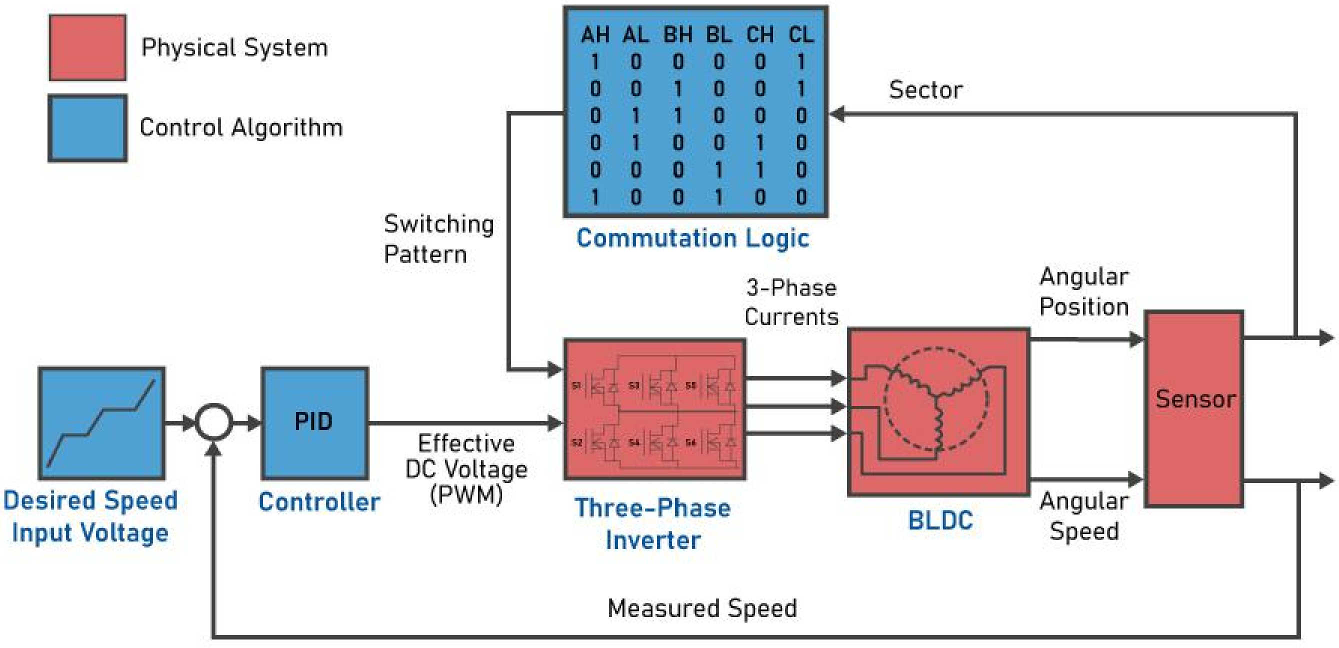
The BLDC sensors provide logic signals which provide position and speed information used by the two control loops. The sensor produces two signals. These signals allow the processor to determine the angular position and speed of the motor. The sensor information allows the processor to detect when the rotor transitions from one sector to another.

The Commutation Logic Table determines the required switching pattern used by the inverter. In the Computational Logic Table, the letters A, B and C represent the three phases of the motor. The high side of the three-phase inverter is labeled H and the low side by L. If the rotor is within the first sector, the commutation logic selects the switching pattern which dictates an on state for the high side switch of phase A and the low side switch of phase C. As the rotor transitions to other sectors, a switching pattern is selected accordingly and sent to the three-phase inverter.

The angular speed is continuously controlled by the feedback loop. The sensor generates a signal which is proportional to the rotor speed. This signal is converted to voltage which is compared to the input voltage by a suitable controller. This adjusts the voltage delivered to the inverter bringing the motor speed close to the desired value.

Table 1. The Effects of Independent P, I and D Tuning

Closed-Loop Response	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Increasing K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increasing K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve



AH	AL	BH	BL	CH	CL
1	0	0	0	0	1
0	0	1	0	0	1
0	1	1	0	0	0
0	1	0	0	1	0
0	0	0	1	1	0
1	0	0	1	0	0

Figure 10. Typical BLDC Motor Control System

5.0 A BRIEF OVERVIEW OF PWM

The principal benefit of PWM as a control technique becomes clear by examining Figure 11. The traditional linear power delivery technique for limiting power simply employs a variable resistance as depicted in Figure 11a. When maximum output is commanded, the driver reduces resistance of the pass element to a minimum. At this output level, losses in the linear circuit are relatively low. When zero output is commanded, the pass element resistance again approaches infinity and losses again approach zero.

The disadvantage of the linear circuit becomes clear in the midrange when the output level is in the vicinity of 50%. At these levels the resistance of the pass element is equal to the load resistance which means the heat generated in the amplifier is equal to the power delivered to the load! In other words, a linear control circuit exhibits a worst-case efficiency of 50% when driving resistive loads at midrange power levels. What's more, when the load is reactive, this efficiency drops even further.

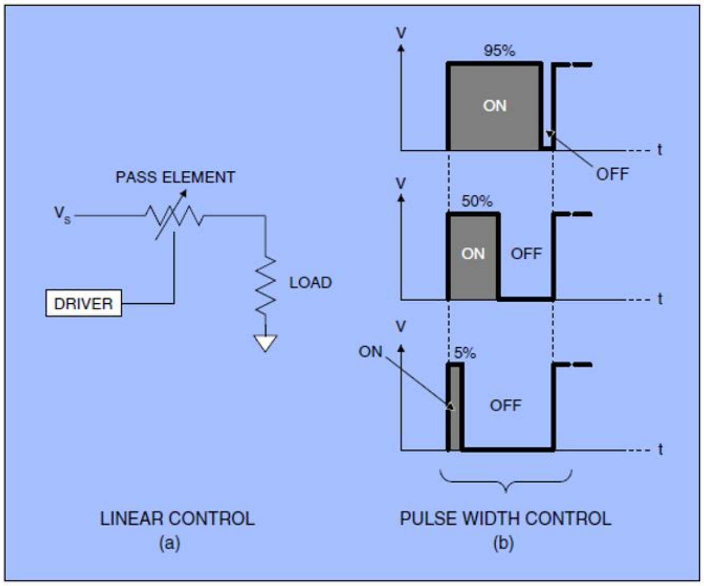


Figure 11. PWM Vs. Linear Control – PWM control in (b) exhibits far lower losses than the traditional linear control technique in (a).

Now consider the efficiencies of the switching PWM operation as illustrated in Figure 11b. In a PWM control system, an analog input level is converted into a variable-duty-cycle switch drive signal, as shown in the figure. The process of switching from one electrical state to another, which in this case is simply between OFF and ON, is called "modulation" – thus the phrase Pulse Width Modulation or PWM.

Beginning at zero duty cycle, which is to say OFF all the time, the duty cycle is often advanced as the motor begins to rotate until it is running at the speed and/or the torque required by the application.

In the case of a PWM control circuit, the losses are primarily due to the ON resistance of the switching FET and the flyback diode which is why efficiencies as high as 80% to 95% are routine. However, at high switching frequencies, the energy required to turn the FETs on and off can become significant.

In addition to enhanced efficiency, PWM can provide additional benefits which include limiting the start-up current, controlling speed, and controlling torque. The optimum switching frequency will depend on inertia and inductance of the brushless motor chosen, as well as the application.

The choice of switching frequency affects both the losses and the magnitude of the ripple current. A good rule of thumb is that in general, raising the switching frequency increases the PWM losses. On the other hand, lowering the switching frequency limits the bandwidth of the system and can raise the heights of the ripple current pulses to the point they become destructive or shut down the brushless motor driver IC. The ripple current pulses are shown in Figure 12.

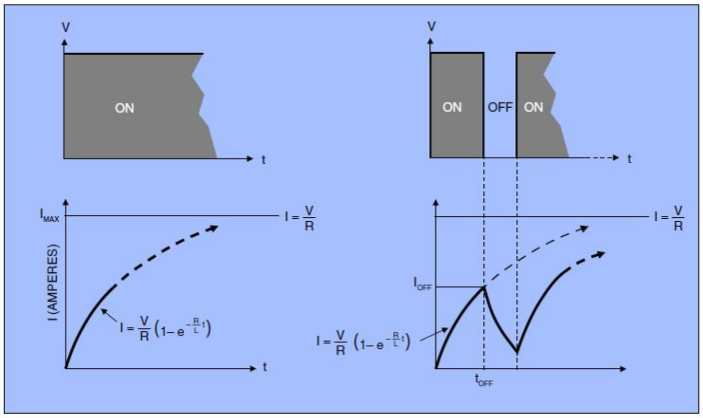


Figure 12. a) Current behavior with a steady-state excitation
b) Current behavior with PWM excitation

One of the most critical operations for a brushless motor — also true for a brush motor — is when power is first applied to the motor while at rest. At that time the rotor is stationary and is delivering no "back EMF" or VBEMF. VBEMF can be expressed as:

$$V_{BEMF} = (K_b)(Speed) \qquad (3)$$

Where:
KB = voltage constant (volts/1000 RPM)
Speed = revolutions per minute (expressed in thousands)

Once a voltage is applied to the motor, the rotor begins turning, generating a VBEMF governed by Equation (3). If we ignore for the moment that we plan to drive the motor with a PWM source and assume the

$$I = [(V-V_{BEMF})/R_m][1-e^{-Rt/Lm}] \qquad (4)$$

Where:
V = the applied voltage
VBEMF = back EMF
Rm = stator resistance (winding pair)
Lm = stator inductance (winding pair)

Note that in Equation (4) the current (I) at any moment is a function of both the back EMF (VBEMF) and the time (t). The current when the motor is stopped (VBEMF = 0) is illustrated in Figure 12a and is a familiar waveform for characterizing the current in any L-R circuit with its rise time governed by the time constant L/R.

Now let's exchange the steady-state excitation voltage for a PWM source, as shown in Figure 12b. The current rises until the first ON pulse ends. When the voltage abruptly falls to zero at the end of the first applied voltage pulse, the current begins to decay towards zero. However, the next pulse will again drive the current upwards, and so forth, so that the current continues to rise. As the motor accelerates, the current waveform will exhibit a sawtooth profile. This sawtooth characteristic is also known as ripple. Because torque is directly proportional to current, the sequence of rising current pulses drives the motor and develops a corresponding torque that accelerates the motor.

The applied voltage, the switching frequency and the PWM duty cycle are three crucial parameters that can be programmed independently. How these variables are selected will affect the behavior of the motor with regard to how fast it will accelerate, and how fast its speed and torque will develop.

6.0 APPLICATION EXAMPLE

Motor drives play a crucial role in numerous aerospace & defense applications, and among these, we will emphasize their significance in missile systems. They are responsible for powering the missile's propulsion and control systems, which typically consist of rocket motors or jet engines.

Here are some key aspects of how motor drives are used in missile applications:

1. Guidance and Control - In missile applications, the guidance and control system are responsible for determining the missile's flight path and ensuring it reaches its intended target accurately. Motor drives are an integral part of this system, as they convert the guidance commands into physical actions that control the missile's propulsion and maneuvering.

The guidance system calculates the optimal trajectory based on various parameters, including target location, missile position, and environmental conditions. It then sends signals to the motor drives, instructing them to adjust the thrust level and direction to steer the missile along the desired path. The control system continuously adjusts these motor drive commands based on real-time feedback from sensors (e.g., gyroscopes, accelerometers, GPS) to maintain the correct trajectory and correct for any deviations.

2. Propulsion System Control - Motor drives are used to control the thrust generated by the rocket motors or jet engines. They regulate the speed and power output of the propulsion system to achieve the desired flight characteristics demanded by the guidance system, such as acceleration, deceleration, or maintenance of a constant velocity.

The motor drive adjusts the rate of propellant consumption and controls the combustion process to vary the thrust level. This control is crucial for different flight phases, such as the initial launch, acceleration, cruise, or terminal guidance phases. For example, during the initial launch phase, the missile may require maximum thrust for rapid acceleration, whereas during a terminal phase, the thrust may need to be reduced for precise target engagement.

3. Fin Actuation - Motor drives are used in fin actuation to control and adjust the fins on various aircrafts and airborne systems such as jets, rockets, missiles, and drones. The primary purpose of fin actuation is to alter the orientation and stability of the aircraft by adjusting the angle of the fins to the desired position. This affects the aerodynamics, allowing the aircraft to change its direction, pitch, roll, or yaw.

Motor drives prove to be crucial components in military aircrafts as they provide the mechanical force needed to move the fins and adjust the desired orientation. The fin actuation system works by processing the aircraft's sensor inputs and comparing them to the desired orientation. By adjusting the angles of the fins, the aircraft can achieve desired changes in its motion, stability, or trajectory.

4. Thrust Vector Control (TVC) - Thrust Vector Control is a critical feature in modern missile systems, especially in guided missiles. TVC enables the missile to change flight direction by adjusting the direction of the thrust. Combined with the use of external fins or control surfaces, TVC uses movable nozzles or other mechanisms in the missile's propulsion system.

Motor drives play a significant role in TVC by actuating these movable nozzles or control surfaces. They receive commands from the missile's guidance and control system, which determines the necessary adjustments to achieve the desired flight trajectory. By changing the direction of the exhaust gases, the missile can alter its orientation and perform maneuvers to navigate through complex flight paths or evade countermeasures.

Motor drives play a crucial role in not only missile applications, but a variety of aerospace and defense systems. Providing precise movement and control, motor drives achieve enhanced performance, and efficiency while maintaining reliability.

7.0 ADDITIONAL PRODUCT INFORMATION

The reliability of motor drives in missile applications is paramount, but the devices that drive these motors are equally as important. Precision control in any type of application requires high power analog to generate movement. Designing power circuitry that is highly reliable and highly stable while balancing electrical and thermal management issues can be very challenging. Apex Microtechnology mitigates and solves these challenges by offering commercial (COTS) solutions reducing complexities for the end customer.

Apex Microtechnology is the industry leader for high-performance power operational amplifiers, pulse width modulation (PWM) amplifiers, integrated power modules, precision ICs and precision voltage references (VRE). Apex products are designed to meet the rigorous demands of military operating environments such as the missile applications discussed earlier.

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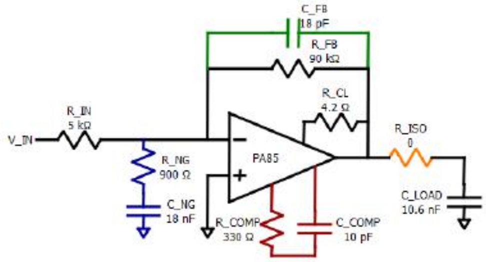

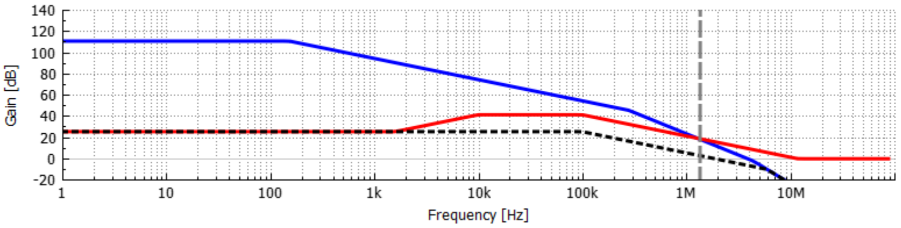

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