Motor-control considerations for electronic speed control in drones

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Introduction

Drones are all around us. The typical drones we hear about or see around us are most often hobby related. However, the potential of using drones for commercial use started several years ago. Primarily, drones are being used were a person might have difficulty reaching or getting a bird's-eye view of a particular area. This spans from agriculture to building maintenance to selling real estate.[1] Another growing use for drones is custom delivery of packages. In the coming years, there is no doubt that many new uses for drones will be discovered. As such, the journey has just begun where drones are now solving real business issues and no longer considered just a toy.

Building a drone

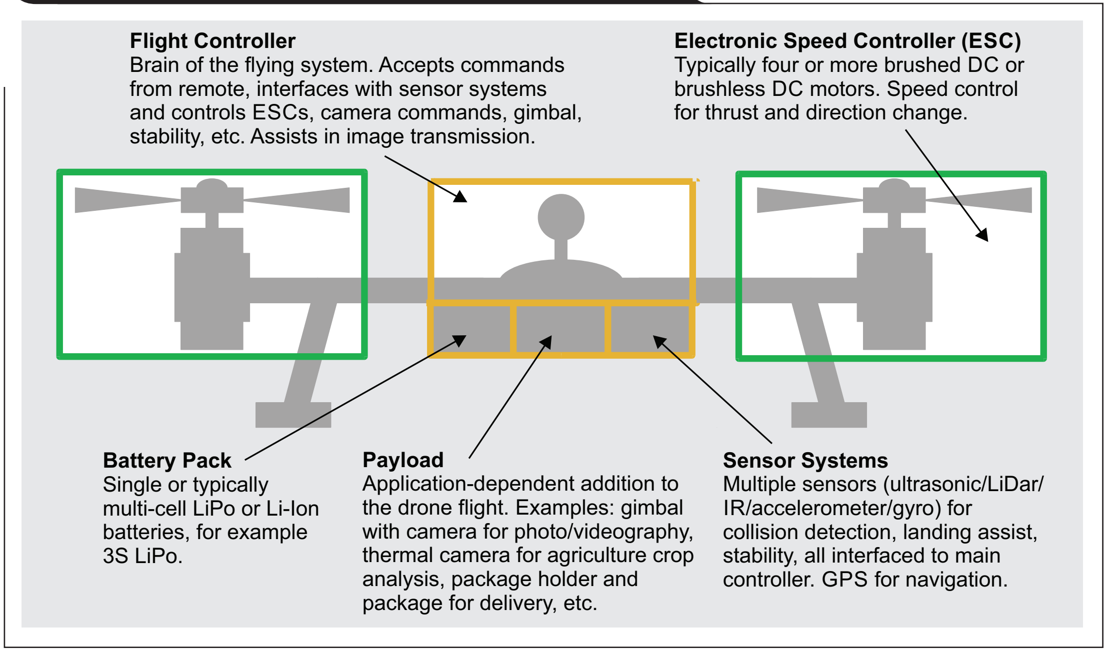
The focus of this article is about how to design an electronic speed controller (ESC) for brushless DC motors. The ESC typically consists of several building modules such as a power stage, current sensing, microcontroller for motor control, and a communication interface to the flight controller (Figure 1).

When designing an ESC for a drone, several considerations are required before deciding on a solution. Some of which are:

- Motor-control topology, depending on the selected motor type
- ESC efficiency versus flight time versus cost
- Chosen battery voltage of the drone
- Flight parameters, such as the maximum speed of the ESC of up to 12,000 RPM or higher (1-kHz electrically or higher)
- Interference such as electromagnetic compatibility (EMC) between the ESC and other modules.

The design considerations in this article are limited to the brushless motors that are generally are used for mid- to high-end drones.

Figure 1. Main modules of a full drone flight system



Flight Controller
Brain of the flying system. Accepts commands from remote, interfaces with sensor systems and controls ESCs, camera commands, gimbal, stability, etc. Assists in image transmission.

Electronic Speed Controller (ESC)
Typically four or more brushed DC or brushless DC motors. Speed control for thrust and direction change.

Battery Pack
Single or typically multi-cell LiPo or Li-Ion batteries, for example 3S LiPo.

Payload
Application-dependent addition to the drone flight. Examples: gimbal with camera for photo/videography, thermal camera for agriculture crop analysis, package holder and package for delivery, etc.

Sensor Systems
Multiple sensors (ultrasonic/LiDar/IR/accelerometer/gyro) for collision detection, landing assist, stability, all interfaced to main controller. GPS for navigation.

System considerations

When selecting a brushless motor, two of the options are:

1. A motor where the three-stator windings are evenly wound and the back-EMF is trapezoidal, called a brushless DC (BLDC) motor, or
2. A motor with sinusoidal winding distribution with a sinusoidal back-EMF, called a brushless AC (BLAC) motor, [also referred to as permanent magnet synchronous motor (PMSM)].

The motor-type selection is typically based on the motor-control algorithm, such as trapezoidal or field-oriented control (FOC). How the motor is wound also affects which control algorithm will provide the best motor efficiency. The chosen control algorithm affects the drone's flight ability based on the algorithm. Sensorless controls are often preferred because they keep design cost low and will improve system robustness versus a mechanical speed sensor.

How a trapezoidal-wound motor will affect algorithm and hardware choices:

- Controlling the motor using a six-step commutation sequence
- Detecting the rotor's magnetic angle in order to commutate at the correct angle, for trapezoidal control it is 60-degree steps
- If sensorless, the commutation angle is estimated by sensing the phase-voltage back EMF

How a sinusoidal-wound motor will affect algorithm and hardware choices:

- Controlling the motor with sinusoidal phase voltages or currents, for example, FOC
- Detecting the magnetic field angle of the rotor within 1- to 5-degree minimum accuracy to ensure maximum torque with the FOC
- If sensorless, estimate the rotor magnetic angle based on the motor's phase voltages and phase currents

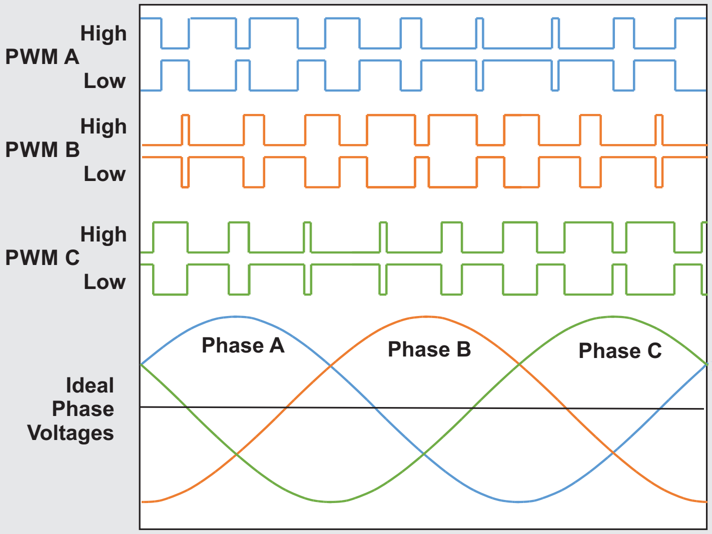
Trapezoidal or sinusoidal control

The pulse-width modulation (PWM) that drives the power stage will be different depending on the control type.

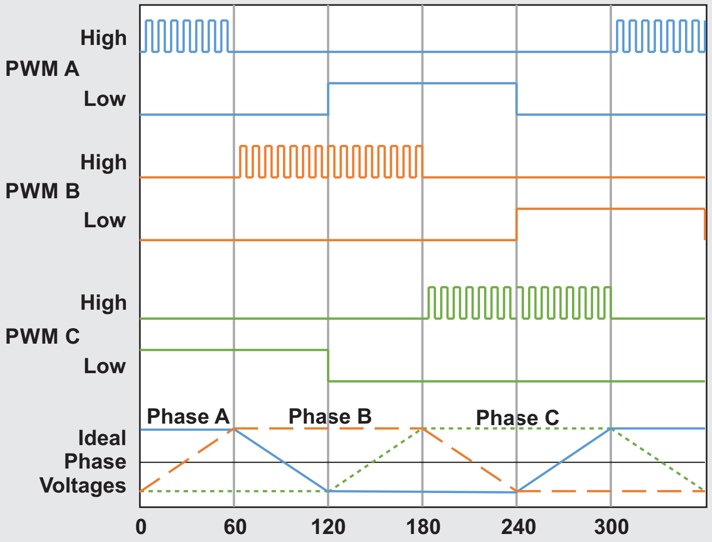
Figure 2 shows typical PWM high-side and low-side patterns for three phases and the corresponding ideal filtered phase voltages after removing the PWM carrier, when running the motor in either trapezoidal or sinusoidal control.

A common problem with trapezoidal control is that a torque ripple and current spike occurs at every commutation. This torque ripple reduces efficiency and can lead to vibrations; both of which can be avoided using sinusoidal control.[2]

Figure 2. Comparison of PWM control methods



(a) Generation of ideal PWM-to-sinusoidal phase voltages with FOC control



(b) Ideal PWM-to-trapezoidal commutation generation used in trapezoidal control

The DC-bus voltage typically used for an ESC ranges from 7.4 V to 22.4 V and the DC link current from the lithium-polymer (LiPo) battery typically ranges from 10 A to 20 A.

The desired PWM frequency for ESC modules is between 30 kHz and 60 kHz because of the relatively low inductance of the high-speed motors and the potential interference to sensor boards. This needs to be considered when choosing the controller because real-time performance of the ESC system needs to be ensured. This can be done by adjusting the full motor-control algorithm in software or hardware.

Open-loop versus closed-loop control scheme

Once the control algorithm has been chosen, the next step is to decide is if the control should be open or closed loop.

In an open-loop control, the synchronous motor (BLDC or BLAC) is blindly driven with a control signal and it is assumed that it follows the designated control action. One issue is that the assumption that the motor has followed the control signal may be erroneous. To ensure that the motor perform correctly, more current than necessary is put on the motor to force the movement. As a result, system efficiency in an open-loop control is reduced when compared to a closed-loop controlled motor.

In closed-loop control, the motor control has the ability to test if the motor moves as expected. If not, the control loop automatically compensates by either reducing or increasing the current. The current is used as a reference value. For trapezoidal control, the measurement of one shunt current is required. For sinusoidal control, up to three shunt currents should be measured.

Whether using a closed-loop control or a sensorless algorithm, current and voltage signals need to be measured so they can be used as feedback signals. Figure 3 shows measurement configurations for both trapezoidal and sinusoidal control.

When using trapezoidal control with a sensorless algorithm, the three-phase voltages are typically used by the sensorless algorithm to calculate the rotor angle. If using a closed-loop current control, one additional low-side shunt is needed. The DC link may also be measured to make further enhancements.

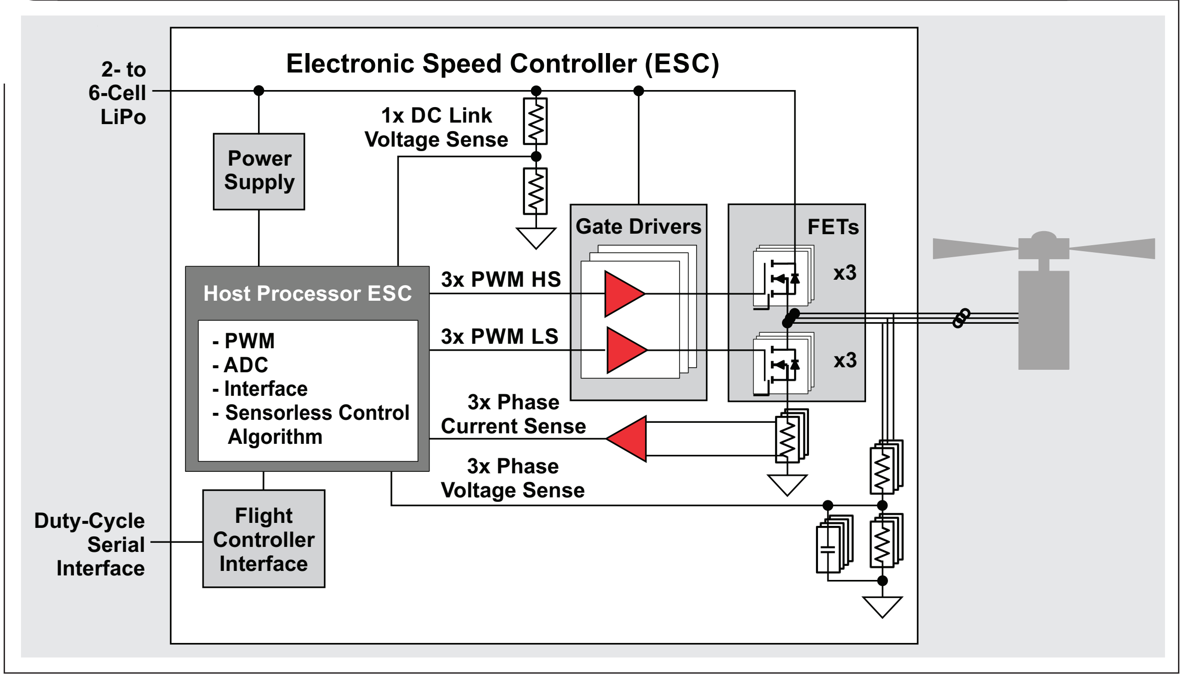
If using a sinusoidal control, there are more considerations because this will impact the system's performance and efficiency. The options are to implement from one to three low-side shunts to sense the currents. For the voltage measurements, the choices are between measuring only the DC link voltage, or the three phase voltages and the DC link voltage.

When using the typical trapezoidal zero-crossing detection algorithm, notice that the dynamic speed performance of the ESC system will be less than a sinusoidal control system.[2] However, trapezoidal control is easier to implement and needs less controller performance.

For both control types, the sensorless algorithm needs to be tuned for best performance over the motor's full speed and torque range. This step improves precision of the angle estimation, which increases ESC efficiency because it uses less current to compensate for angle errors.

When using closed-loop control, it is important to tune the algorithm to fit the system requirements to enable the motor to run stable at very high speeds (12 kRPM). To achieve this high speed, current control is needed to avoid instability of the control loop.

Figure 3. ESC module in a drone using a brushless motor with sensorless control



To improve system performance, it is important to optimize the ESC's current and speed controller for specific motor and system requirements. With the TI InstaSPIN™-FOC technology, designers can identify, tune and fully control any type of synchronous or asynchronous motor control system.[3] The following example uses FOC control.

Step-response optimization based on time domain

To optimize the system, a step response is generated for both the current and speed controller. This step response can then be optimized to improve system performance. Examples of a cascaded PI-speed and PI-current control are shown in Figure 4.

Assumptions for FOC control

In FOC control, the idea is to generate a step response in the I_d current controller to be almost independent of load torque changes. The I_d step response can also be used as an estimate of the I_q step response. Doing this removes the need to have a load emulator like a dynamometer when trying to generate the step response in I_q. I_d and I_q are Park's transform-defined currents for a FOC motor control.[4]

When adjusting the step response, tune both the current and speed PI controllers. Start first by adjusting the current controller when the user has defined its optimum step response. Once this is done, repeat the same process for the speed controller. The step-response data generated for this article used the LAUNCHXL-F28069M evaluation platform with the BOOSTXL-DRV8305EVM evaluation module. The motor used was a Turnigy Multistar 1704-1900Kv.

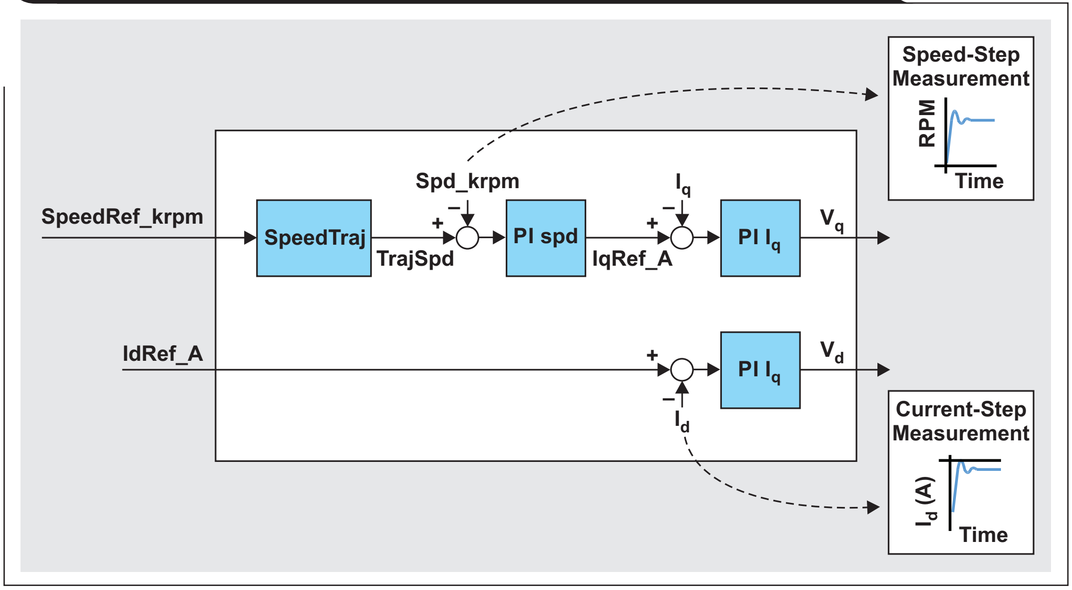
When running the controller at very high speeds, above 1-kHz electrical frequencies, it is important to know how much time the current controller has between each control change because it needs to be stable before the next change occurs. Use Equation 1 to translate the electrical frequency into the maximum RPM.

$$\begin{aligned} \text{MAX}_{\text{RPM}} &= \frac{f_{\text{Voltage}} \times 60\text{ s}}{\text{Pole\_Pairs}} \\ &= \frac{1{,}000\text{ Hz} \times 60\text{ s}}{6} = 10{,}000\text{ RPM} \end{aligned} \quad (1)$$

where f_{Voltage} is the electrical Hz/s frequency of the motor and Pole_Pairs is the number of magnetic pole pairs of the motor.

To ensure stable high-speed control with 1-kHz electrical frequency, keep in mind that the current controller has less than 1 ms to settle before the next current change should be applied from the speed controller. The current step response needs to settle quicker than the time it takes from one speed change to the next. Without this, the speed controller will be correcting the currents based on measurements obtained while the current is still unstable.

Figure 4. Cascaded speed and current controller with FOC algorithm



To ensure stability, the step response can be used to show how fast the current settles after a change. With the hardware and software setup for the C2000™ microcontroller, the step-response curve in Figure 5 was generated in real time for the ESC system.

With this tuning, the current-controller bandwidth ($f_{-3\ \mathrm{dB}}$) is set to approximately 1000 Hz. Equations 2 and 3 show the consideration: $3 \times \tau \Rightarrow$ 95% settled $\Rightarrow$ ~0.5 ms.

$$\tau = \frac{0.5\ \mathrm{ms}}{3} = 0.166 \tag{2}$$

$$f_{-3\mathrm{dB}} = \frac{1}{2\pi\tau} \approx 1000\ \mathrm{Hz} \tag{3}$$

where τ is the time constant and $f_{-3\mathrm{dB}}$ is the 3-dB bandwidth of the current controller.

PI controller values were used to generate the speed-step response in Figure 6. This step response shows how fast the controller can react to a reference speed change, which is controlled with almost no overshoot. Here an overshoot in the speed response becomes excess energy, which can be avoided by optimizing the step response to the customer's system requirements. Something else to remember is to adjust this controller using a motor with a propeller (the load for the motor). The propeller changes the inertia of the system and needs to be taken into consideration when running the full system. The maximum acceleration of the motor can be estimated from the step response shown in Figure 6, where the step change from 550 RPM to 900 RPM takes around 27 ms, which is an acceleration rate of about 13 kRPM/s. This maximum value depends on the system's peak current capability and the desired dynamics of the control loop.

Tuning the speed controller is critical, especially at very high speeds, to ensure that the ESC can run to the maximum speed. Any instability needs to be addressed by adjusting the speed controller to obtain acceptable system performance.

Conclusion

When using sensorless FOC for an ESC in drones, even high-speed motors can run at maximum speed using TI NexFET™ MOSFETs, the DRV8305 three-phase gate driver, and a C2000 processor with InstaSPIN-FOC technology. This configuration has the necessary current and voltage rating typically used for ESCs. It has been proven that the boards can run a motor with 6 pole pairs at 12,000 RPM using the sensorless algorithm of InstaSPIN-FOC to give the user maximum system performance. For user evaluation, it is possible to use TI software and hardware to drive the motor, which requires minimum user effort to spin the motor and to optimize the system for best overall performance.

Figure 5. Current step response showing no overshoot at high bandwidth

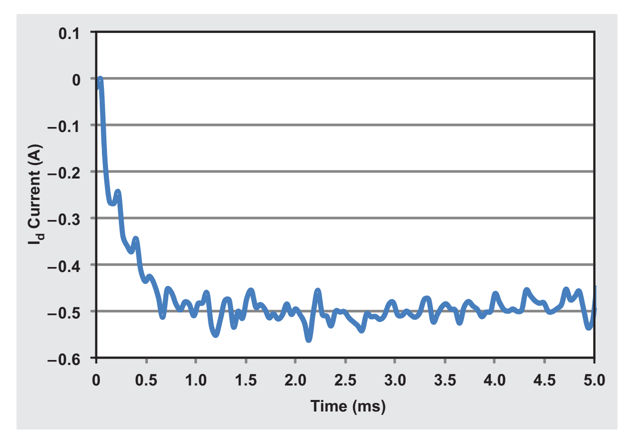
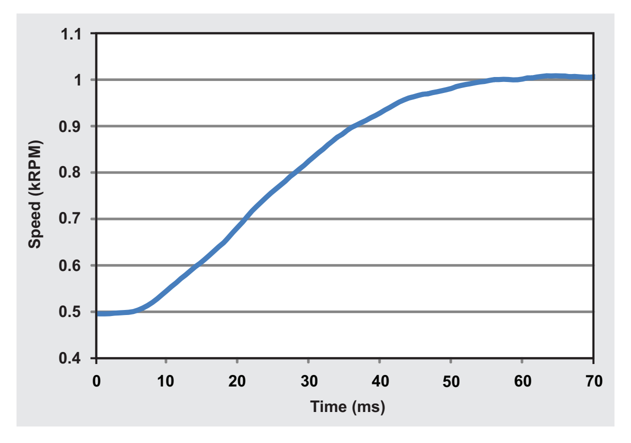


Figure 6. Speed-step response showing slight overshoot



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2. Dave Wilson, "Navigating the complexities of motor control," Motor Control Compendium, 2010-2011, pp 137-149.
3. TI InstaSPIN™ Motor Control Solutions—InstaSPIN-FOC, Texas Instruments microcontrollers (MCU)
4. Dave Wilson, "Navigating the complexities of motor control," Motor Control Compendium, 2010-2011, pp 163-177.

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