**Report Breakdown and References**

This section lists the resources used in the other pages.

**Issue #1: Detecting rotor position at start-up and low-speeds**

* <https://e2e.ti.com/blogs_/b/industrial_strength/posts/start-your-bldc-journey-with-motor-startup-part-iii-initial-position-detection-ipd>

**Notes #1: Sensing Rotor Position using Back-EMF**

* Position and Speed Control of Brushless DC Motors Using Sensorless Techniques and Application Trends

**Notes #2: PI-Controller (Analogue) or Microcontroller (Digital)**

**Notes #3: Methods to Control Inverter: (the math)**

* <https://www.youtube.com/watch?v=yEJpAB95mrY>

**Notes #4: Design New control system for Brushless DC Motor Using SVPWM (Report)**

* Contains the mathematics and timing considerations.

**Notes #5: How to Make Advanced BLDC Motor Controllers**

* https://resources.altium.com/p/build-advanced-brushless-motor-controller

**Notes #6: Braking Techniques**

* <https://thesixtech.com/blogs/thesix-blog/bldc-motor-braking-techniques-part-1>
* <https://www.youtube.com/watch?v=yEJpAB95mrY>

**Notes #7: Current Sense Amplifiers**

**Notes #8: New Approach to sensorless control method for brushless DC Motors.**

* Tae-Sung Kim, Byoung-Gun Park, Dong-Myung Lee, Ji-Su Ryu, and Dong-Seok Hyun

**Design #1: Space-Vector PWM Specifications:**

* https://electrotech4u.blogspot.com/2011/07/implementation-of-space-vector.html

**Design #2: ADC Parameters to look for**

* **NXP – How to increase the Analog-to-Digital converter accuracy in application**

# Issue #1: Detecting rotor position at start-up and low-speeds.

**Problem**: At low speeds, FOC has a problem with detecting the rotor position because the back emf is low. Unlike PMSM, where the back-emf is sinusoidal, BLDCs have a trapezial back-emf, resulting in a low signal at slow speeds. Industry has two solutions to the startup problem:

* **Align-and-Go**: Force a voltage along one phase to force the rotor into a known state.
* **Initial Position Detect**: Used when we cannot move the propeller or wings. We can get the position of the rotor by locating the smallest motor winding inductance using voltage pulses and current saturation.

For the low-speed problem, TI stores several previous angles in firmware to track its position. If we can predict its position, then using the Back-emf reading, we may be good. Another solution I thought of is to add an OP-Amp gain stage with high bandwidth to increase the differential signal of the shunt, that way even if the back-emf is small, we can amplify it suitably.

**Solution**: For simplicity, we will use Align-and-Go for the start-up and move from an open-loop system to a closed loop once reaching higher speeds.

# Notes #1: Sensing Rotor Position using Back-EMF

Back-emf detection is the most common sensor-less method to determine the rotor position. There are two types of techniques:

* **Direct**: The back-emf of the floating phase is sensed and its zero crossing is compared with neutral point voltage. This suffers from high common mode voltage and high frequency noise due to the PWM drive, so it requires low-pass filters and voltage dividers. These methods are called.
  + Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing
  + PWM Strategies
* **Indirect:** Since filtering introduced commutation delay at high speeds and attenuation causes reduction of signal sensitivity at low speeds, the speed range is narrowed in the direct back-emf detection. To reduce switching noise, indirect methods work best.
  1. Back-EMF Integration
  2. Third harmonic Voltage Integration
  3. Free-Wheeling Diode Conduction or Terminal Current Sensing

**Method 1: Terminal Voltage Sensing (Simplest, sucks at low-speed)**

* Detect the instant at which the back-emf of the unexcited phase crosses zero. The zero crossing triggers a timer (RC Constant or something) so that the next inverter commutation (state switch) occurs at the end of this timing interval.
* The detection formula for an unexcited phase is the back-emf plus half the supply voltage. Therefore, **zero-crossing occurs when the voltage of the floating phase is ½ VDC.**
* To reduce the high frequency noise, low pass filters are used. To avoid the delay associated with analogue filters, PWM can be used to measure the terminal voltages; the true phase back-emf signal can be directly obtained from the motor terminal voltage by choosing the PWM and sensing strategy. This would provide advantages such as no sensitivity to switching noise, no filtering, and good motor performance over a wide speed range.
* The cost for this method is the noise sensitivity to detect the zero crossing and degraded performance over wide speed ranges unless the timing interval is a function of rotor speed. Typical rotor detection is from 20% of rated speed (1k-6k rpm).
* Optimization:
  + Assuming motor speed is somewhat constant, the commutation points can be predicted, and position can be found using a low-pass or band-pass filter by using only a single phase.
  + The ZCP can be indirectly detected by using the difference of the line voltages.
  + Sensorless commutation can be done by using a Phase Locked Loop and sensing the phase winding back-emf voltages.
* Start-to-Finish Idea:
* At low-speeds, the back emf detection works poorly because it is proportional to the motor speed. But by using a start-up procedure, such as align-and-go or initial position detection, it can still work. The idea is to start spinning the rotor as an open-loop system, rather than closed-loop.
* At high-speeds, the parasitic resonance of the winding inductance and capacitance can cause false zero crossing detections. The solution is to detect the back-emf during the on-time at high duty cycle, so that there is enough time for the resonant transient to settle down.

TLDR; we are predicting commutation points and switching the mosfets based on that result.

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**Method 2: Third Harmonic Voltage Integration**

* Use the third harmonic of the back-emf to determine the commutation instants.
* Requires only a small amount of filtering, not sensitive to filtering delays, and performs well over wide speed range. Can be detected in low speeds.
* There are three methods to extract the third harmonic component of the back-emf.

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* Only Vsh is suitable for the third-harmonic back-emf sensorless operation, but an open-loop starting procedure needs to be employed.
* Optimization:
  + Use a PLL, where the free-wheeling diode conduction takes place right after commutation. The key advantage is the wide speed range of operation, but the downside is the offset error and position error.

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**Method 3: Free-Wheeling Diodes Conduction Detection**

Not good.

**Method 4: Back-EMF Integration Method**

The commutation instant is determined by integrating the unexcited phases back-emf. When the integrated value reaches the predefined threshold value, the phase current is commutated.

If flux weakening operation is required, this can be done by changing the threshold voltage.

Integration reduced switching noise and automatically adjust for speed changes, but sucks at low speed.

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The waveform Is fed into an integrator whose output is compared to a pre-set threshold. Using an integrater reduceds the switching noise sensitivity and automatically adjusts the switching instants according to changes in the rotor speed. Thirdly, the back-EMF integrating method is a technique applying the principle that integration is constant from Zero Crossing Point (ZCP) to 30°

**Method 5: PWM Strategies**

* **120° PWM Technique (Classical Solution)**

Low switching losses at the inverter side but higher harmonic contents, resulting in losses on the motor side.

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* **Virtual Neutral Point Elimination**

Most motors don’t have a neutral wire, therefore we can build one that will be theoretically the same potential as a real one. The virtual neutral point fluctuates at the PWM frequency, therefore Voltage dividers and low-pass filters must be used because the common-mode voltage and high frequency noise is high. When eliminating the virtual neutral point, filtering is required and the ZCP of the floating phase can be got.

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* **Low Speed Applications**

At low speed the backemf is too small, so to fix this use complementary PWM.

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* **High Speed Applications**

At high speeds, the ZCP is missed because the series current limiting resistors and microcontroller pin capacitance cause a high time constant to form, causing a long falling edge of the signal. If the PWM duty cycle is high enough such that the off time is less than the falling edge time, the sample result is wrong because the RC circuit has not been discharged. A way to minimize this is to use a smaller resistor in parallel with the current limiter and a diode to block the charging current from going through the parallel resistor. This solution has worked successfully for 300V/30k RPM air blowers.

* **Small Power Applications**

Power consumption and heat loss is significantly reduced.

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* **Direct Current Controlled PWM Technique (Hysteresis Current Control)**

This technique uses two phases instead of three to drive the DC Motor. Several issues are in this design, such as asymmetrical voltage PWM, unconventional PWM drive schemes. Basically, rather than using voltage levels, you are using current to drive the mosfets (Hysteresis Current Control). Used in AC induction motors but can be applied to BLDC.

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Sliding Mode Observer (Track Rotor Position)

Extended Kalman Filter (computationally Predict)

**Implementation of Back-EMF Control Techniques**

Eliminating the virtual neutral point is best for us because it provides a wide speed range, used in both high and low voltage application, and has a faster startup. Also, because its simple to build.

For startup, it might be good to do a short pulse train to the motor and determine from back-emf the rotor position.

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# Notes #2: PI-Controller (Analogue) or Microcontroller (Digital)

The PI Controller is a popular method to reduce the steady-state error of a motor controller. This is important because we want the real signal to match the ideal as closely as possible. The PI Controller can be processed continuously or discreetly. Using an analogue system is faster and has a higher bandwidth, but it is susceptible to noise and interference, which is likely going to occur due to the large voltages/currents being inverted by nearby mosfets. Moreover, an analogue system requires extra board space, more components, and fine-tuning, resulting in a higher dollar-cost and longer development time. Cheaper and quicker is a digital implementation via microcontroller. One with a dedicated ADC channel with a sufficiently high sample frequency and resolution would be best.

A diagram of a motor

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For this project, we will implement a digital PI Controller on a microcontroller to reduce board space, decrease dollar-cost, reduce BOM size, and lower development time.

# Notes #3: Methods to Control Inverter

There are many methods to toggle the MOSFETs in an inverter circuit. There are several techniques to perform the action of spinning a rotor.

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Method 1: Conventional PWM

Method 2: Sinusoidal PWM

* Better than conventional PWM, but has maximum voltage of ½ VDC to 2/3 VDC. Because this is limited by the 6-step commutation.

Method 2: Space-Vector PWM

* The main idea is to apply a PWM signal at non-set angles to reduce torque ripple. Ie 48° rather than 30°.
* This is done by controlling the duty cycle of a PWM signal to a phase to increase/decrease the magnitude of the vector.
* There are three vectors - U,V,W – one for each half-bridge rectifier. The magnitude of the vector is controlled by the duty cycle, while the rate of speed is controlled by the frequency.
* The sum of the three vectors result in a phasor that rotates perfectly along with the rotor.
* Improvement over sinusoidal PWM by having max voltage of VDC/sqrt(3), due to not requiring 6 steps.
* Phase voltage is 2/3 VDC

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Method 3: third harmonic injection sinusoidal PWM

* Better than SVPWM because it increases the max voltage of the motor voltage.
* Rather than outputting a square wave, we can output a sin wave plus the third harmonic.
* With a 60° phase shift, the max voltage because VDC/2
* The third harmonic cancels itself out due to common-mode voltage and the oscilaltions, so the winding doesn’t see the harmonic, only the sine wave.
* The phase voltage is 15% higher than SPWM.
* Very hard to implement in hardware, it can be a graduate level project all on its own.

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# Notes #4: Design New control system for Brushless DC Motor Using SVPWM

**Synopsys**: This procedure depends on motor speed feedback only. This control system was shown to be an improvement from the conventional system under different loads and speeds

“The BLDC motors are rapidly gained popularity and become widely used in various consumer and industrial systems because of their better characteristics and performance. BLDC motor has several advantages over conventional DC motors and some of these are High efficiency, higher dynamic response, better speed versus torque characteristics, Higher speed ranges, Long life operating, less noise operation, Less electromagnetic interference, Compact size, and better heat dissipation.”

“BLDC motor is type of permanent magnet synchronous motor (PMSM) which is driven by direct current and it accomplishes electronically controlled commutation system to produce rotational torque in the motor by changing phase currents depending on the rotor position.”

* **Control System of BLDC Motor Drive**: There are three parts to this system: the BLDC, three phase inverter, and control system (PWM technique and speed controller).
* Feedback signals: Three Hall Sensors and one speed motor signal.

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* Speed Controller: PI Controller because it reduces the steady-state error.

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* New Control System Design Procedure: The voltage phasor is given by the following equation

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* Switching pattern of SVPWM:

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* Modulation Index: The amount of dc voltage being delivered to the motor -
* Time duration of each phase can be mathematically determined,

# Notes #5: How to Make Advanced BLDC Motor Controllers

**Synopsys**: Altium has went over how to design an advanced motor controller that would be useful to reference.

The image below is how their motor is driven. The mosfets will require gate drivers to toggle sufficiently quick. Using a half-bridge gate driver is best because it will prevent accidental turn ons causing shoot through.

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Two methods of driving the motor: Sinusoidal and Trapezoidal. You can use either driving strategy for either PMSM and BLDCs but only PMSM with sinusoidal driving will provide constant torque.

Driving frequency vs Control frequency: Driving referes to PWM frequency, while control refers to the the complete cycle of the control system. A higher driving frequency is best, but it will require faster PWM modules, gate drives, transistors, etc. higher frequency can help reduce EMI issues caused by lower frequencies.

Rotor position: either hall-effect sensors, or back emf.

Winding current allows us to measure torque indirectly. We need to measure the current draw of all three phases.

PWM Characteristics: 20kHz is good enough.

Computational power: Arm M0 or better

Power Stage: Three nMOS half-bridges for switching the current. Standard silicon-carbide based components is best. Choose a Low Rds(ON) at selected working Voltage (12V)

* Be sure to use pulse tolerant resistors. This section of the circuit will be continually switching ~1 to 2 A, so significant current pulses will be generated.
* Add a high resistance pulldown resistor on your gate. This will shut down the transistors in the event of any failures, although it might impact performance if not done correctly.

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Gate Drivers:

* The offset voltage is the max voltage the gate driver can provide to offset the high drive transistor. Ensure offset voltage is higher than bus voltage.
* Gate driver should have a range of 10 to 20V, but make sure it doesn’t exceed the max gate voltage (typ 15V). use a zener to limit the gate voltage.
* Consider the deadtime of the half-bridge.

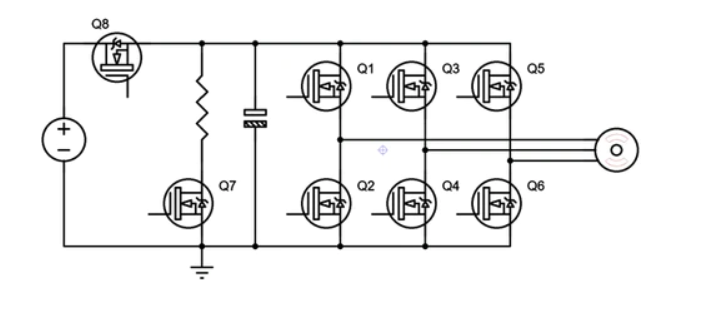
Routing:

* Heat management: use multiple power planes and use thermal vias (0.5mm hole 1mm diameter)
* Use polygons for anything related to power signals as a minimum
* Always consider return paths

Ensure Dangerous areas are marked.

# Notes #6: Braking Techniques And Power Supply

**Synopsys**: Dynamic braking is when you shutdown the supply voltage and enable a resistor in parallel with the motor to release the energy. Probably best to put a Schottky diode in series with the resistor to help with the energy dissipation.



The other braking technique is regenerative braking, which is not applicable for our application. It uses the torque produced by the load to charge a battery. It is also more expensive.

For power, the motor can be supplied by a three-phase AC signal, that is then rectified using diodes. Another method is straight DC. We are using DC because AC power is usually not available on robots. If AC power is desired, a diode rectifier is designed by selecting a diode that has a fast switching time and small forward voltage drop.

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# Notes #7: Current Sense Amplifiers

**Synopsys**: Current Sensing can be done either on the high-side (before the load) or the low side (after the load). We will be using both styles of sensing to determine the bus voltage/current, phase voltage/current, and back-emf. This section will discuss the requirements of the circuit.

# Design #1: Space-Vector PWM Specifications

**Synopsys**: SVPWM is a control algorithm to generate three phase pure sine AC Voltage. This technique uses more available DC Supply voltage (15% More voltage output), has less harmonic distortion, and has more degrees of freedom verses the standard method.

**Basic Theory:** Eight possible switching states for 3-phase inverter can be realized. There are 6 active switching states and two non-active states. The resultant output voltage (“reference voltage”) that goes into the motor can be generated by sampling two adjacent vectors inside the hexagon within time period Ts = 1/Fs

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**Design:** SVPWM can be built by following three steps: Determine |Vref| and angle (θ); Determine switching times T1, T2, T0; Determine the switching sequence.

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1. Determine |Vref| and angle (θ):

(M is modulation index = [0, 0.866])

~ When Vref is made using 50Hz at 2.5ms, the angle is 45°

1. Sampling time is given by:

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Note: there are several formulas to calculate the time durations.

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1. The switching sequence:

There are many different Switching sequences, but we will use the Symmetric Sequence SVM Algorithm due to the low THD.

# Design #2: ADC Parameters to look for

**Synopsys**: This article explains the basics and key parameters. It also lists some error sources and how to increase the accuracy from a system point of view.

**Basics:**

* To get a closer digital result from an analog signal, a higher resolution of ADC is needed.

**Terminology**:

* Reference Voltage:
* This is the voltage the analog input is compared to produce the digital output.
* The digital output is the ratio of analog input with respect to this voltage.
* Digital Value = Analog Input Voltage/(VREF Voltage) \* 2^n (n is number of bits)
* Resolution: with a 3.3V reference, it is 3.3/4096 = 0.805 mV
* Quantization: Ideally, any analog input can be ½ LSB away from the digital code, therefore the quantization error is 0.5LSB
* Sampling Frequency: the speed to convert the analog signal to digital signal. This must be at least 2x faster than the analog signal frequency (Nyquist sampling theory). Information will be lost if sampling slower.
* An adc with conversion time of 10µs can sample an analog signal with a 20µs time period.

**Errors:**

* Offset Error: The difference between the actual and ideal first transition voltages (see Zero-Scale Error).
* When the analog input is between 0.5LSB and 1.5LSB, the digital output should be ideally still until the first transition occurs at 0.5LSB. This can be calibrated by firmware.
* Gain Error: Deviation between last actual transition and last ideal transition. This happens when the analog input is less than the reference voltage minus half the LSB.
* Differential Linearity Error: maximum deviation between actual and ideal steps.
* Integral linearity Error
* Total unadjusted error
* Whole system errors:
* Reference voltage noise
* Analog-Input Signal Noise
* ADC Dynamic Range
* Analog-Signal Source Resistance
* Temperature
* I/O Pin Crosstalk
* Put a ground rail between analog and digital signals

**Increasing ADC Accuracy:**

# Notes #8: A New Approach to Sensorless Control Method for Brushless DC Motors

**Synopsys**: BLDC motors have a higher power density than other motors because they experience no copper losses due to using the magnetic field, which leads to a lack of mechanical commutation mechanisms.

Conventional Strategies:

* Open-phase current sensing (detecting the conduction of freewheeling diodes on transistors)
* Third-Harmonic Back-Emf (remove components of the signal by summing the three phase voltages)
* Back-Emf integration (integrate from ZCP to 30°)
* Open-Phase Voltage Sensing

The strategy proposed here is called the *unknown input observer*

This equation is the motor equation

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The unknown observer can be obtained as follows:

1. First Line-to-Line Back-EMF estimation using unknown input observer. In the following equation, Iab and Vab can be measured, and the back-emf is the unknown.

This equation can be re-written into a “simpler matrix

1. This method can detect the position of the rotor within the first 60°, rather than picking up speed;.