Demystifying BLDC motor commutation:
Trap, Sine, & FOC

Matt Hein
Applications manager, brushless-DC motor drives
Agenda

• Introduction

• BLDC motor basics

• Basic commutation (trap)

• Sensored & sensorless

• Advanced commutation (Sine & FOC)

• Summary
Matt Hein introduction

• Work
  – Applications engineer in motor drives (4 months)
  – Systems engineer in motor drives (3.5 years)
  – Product marketing engineer in motor drives (3 years)
  – Product marketing manager in motor drives (1 year)
  – Applications manager in motor drives (1 year)

• Personal
  – Rollerblading
  – Travel (not so much right now)
  – 11-month-old son at home

Some of my writings:
  • Seven things that only an analog engineer would understand – e2e.ti.com
  • Brushless-DC motor systems for the uninitiated – Planet Analog
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Motor operation

- Electrical power is converted into mechanical power

\[ P_{IN} = V_S I_M \]
\[ P_{OUT} = \tau \omega \]
Motor operation

- Commutation is mechanical
- **Advantage:** Easy to drive
- **Downside:** efficiency, power, wear-out, sparking

- Commutation is electrical
- **Advantage:** Efficiency, power
- **Downside:** System needs to apply signal to commutate motor

Image credit:
(1) Morai Motion, Brushed vs Brushless DC Motors. https://microlinearactuator.com/brushed-vs-brushless-dc-motors/
Motor construction

Sinusoidal motors

Trapezoidal motors

BEMF waveform
Motor construction

Sinusoidal motors

Trapezoidal motors

Need a way to tell them apart? Hook up a scope probe between two outputs and spin it with your fingers!
Motor construction

Sinusoidal motors

- Ideally driven with a sinusoidal current

Trapezoidal motors

- Ideally driven with a trapezoidal current

More on this later!
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Motor operation

Rotation position defines the direction of current!

- Commutator reverses flow of current to make sure that the magnetic field generated on the rotor is always opposed by the field on the stator

Image credit:
(1) Morai Motion, Brushed vs Brushless DC Motors, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/
Motor operation

Step 1: Figure out where the rotor is
Step 2: Apply a magnetic field to move the rotor

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- Step 1: Figure out where the rotor is
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Sensored brushless-DC motor control

• Step 1: Figure out where the rotor is
• Step 2: Apply a magnetic field to move the rotor

Figure out where the motor is through a position sensor

Hall-effect Sensor
Sensored motor control

N = H
S = L

Hall A
Hall B
Hall C

1 2 3 4 5 6
## Sensored Trapezoidal Motor Control

### Phase Configuration

<table>
<thead>
<tr>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>L</td>
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</table>

**Phase Allocation**

<table>
<thead>
<tr>
<th>Phase U</th>
<th>Phase V</th>
<th>Phase W</th>
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<td>Z</td>
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<tr>
<td>+</td>
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</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

**Symbol Indicators**

- **N = H**
- **S = L**

---

*Texas Instruments*
## Trapezoidal control (Trap)
Also called: 6-step, block commutation, 120°, 150°

### Advantages
- Highest maximum speed
- Great for delivering maximum torque
- Lowest switching losses
- Easiest implementation

### Disadvantages
- Not great noise performance
- Efficiency not the best

<table>
<thead>
<tr>
<th>Phase U</th>
<th>+</th>
<th>+</th>
<th>Z</th>
<th>-</th>
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<tr>
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</tr>
<tr>
<td>Phase W</td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>Z</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
Brushed-DC vs. sensored brushless-DC
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Sensored brushless-DC motor control

Hall-effect Sensor

Figure out where the motor is through a position sensor

Disadvantage: increased cost

- Step 1: Figure out where the rotor is
- Step 2: apply a magnetic field to move the rotor
Sensorless brushless-DC motor control

- Step 1: Figure out where the rotor is
- Step 2: apply a magnetic field to move the rotor

Figure out where the motor is through Back-EMF
What is Back-EMF?

Back-EMF is a sinusoidal or trapezoidal voltage generated on the motor while it is spinning.

Spin the motor with your fingers to create a back-EMF signal.
Sensorless brushless-DC motor control

Back-EMF “zero crossing” can be used as a commutation signal

This coil is not being driven
Sensorless brushless-DC motor control

Detecting Back-EMF:

1) Measurement

Advantage: Simplicity

Disadvantage: Performance, need to have open window on phase to measure

Back-EMF measurement does not allow for sinusoidal or FOC control
Sensorless brushless-DC motor control

Detecting Back-EMF:

2) Estimation & Calculation

Advantage: Performance, can achieve sine/FOC

Disadvantage: Complexity, calculation, need to know motor parameters

\[ v_s = Ri_s + L \frac{d}{dt}i_s + e_s \]
Disadvantages of sensorless?

Where is Back-EMF (sensorless techniques) not going to work?

Applications that require torque at zero speed

Servo applications → always sensored!
How do we start a motor sensorlessly*?

*not a real word, but it should be

Starting a motor:

• We need to figure out where the rotor is so that we can apply a magnetic field to move it
How do we start a motor sensorlessly*?

*not a real word, but it should be

**Align / Blind Start**

- Force a magnetic field on the motor, the motor will align to this field
- The motor may spin backwards

**Initial Position / Speed Detect**

- Measure position through high frequency pulses or speed through back-EMF detection
- Drive motor given initial condition
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Motor performance

- Commutation is mechanical
- Can’t adjust drive method beyond 100% ON/OFF

- Commutation is electrical
- Can drive motor with trapezoidal (100% ON/OFF) or a smoother sinusoidal waveform

Image credit:
(1) Morai Motion, Brushed vs Brushless DC Motors, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/
Sensored trapezoidal

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Phase U</td>
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<td>Z</td>
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<td>+</td>
<td>Z</td>
<td>-</td>
</tr>
<tr>
<td>Phase W</td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>Z</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Current U</td>
<td>+</td>
<td>+</td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>Z</td>
</tr>
<tr>
<td>Current V</td>
<td>-</td>
<td>Z</td>
<td>+</td>
<td>+</td>
<td>Z</td>
<td>-</td>
</tr>
<tr>
<td>Current W</td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>Z</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

DRV5013

Hall A

Hall B

Hall C

N = H
S = L

Current U
Current V
Current W

Phase U
Phase V
Phase W

Texas Instruments
Sensored sinusoidal

Phase U
Phase V
Phase W
Current U
Current V
Current W

DRV5013

Hall A
Hall B
Hall C

N = H
S = L
Sinusoidal control (Sine)
Also called: 180° - *always ask if your sine control is really 180°!*

**Advantages**
- Low noise
- Easier to implement than FOC

**Disadvantages**
- Switching losses
- Not great dynamic load performance
- Lower maximum speed
Field-oriented control (FOC)
Also called: vector control, “why is this so complicated”

**Advantages**

- Highest power output
- Lowest noise
- Best torque ripple
- High motor speed (field weakening)
- Maximum motor efficiency (MTPA)

**Disadvantages**

- Computation complexity (especially when sensorless)
- Coding experience needed
- Switching losses
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor

Diagram showing the control flow and components involved in a field-oriented control system.
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
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Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor
Clarke transform

\[ \alpha = U + V \cos 120^\circ + W \cos 240^\circ \]
\[ \beta = V \sin 120^\circ + W \sin 240^\circ \]
\[ \alpha = U + \frac{1}{2} V - \frac{1}{2} W \]
\[ \beta = \frac{\sqrt{3}}{2} V - \frac{\sqrt{3}}{2} W \]
Park transform

\[ d = \alpha_d + \beta_d \]
\[ d = \alpha \cos \theta + \beta \sin \theta \]
\[ q = \alpha_q + \beta_q \]
\[ q = -\alpha \sin \theta + q \cos \theta \]
Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor

\[
\begin{align*}
\alpha, \beta & \quad u, v, w \\
d, q & \quad \alpha, \beta \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Inverter} \\
& \quad \text{PWM Vu, Vv, Vw} \\
& \quad \text{Encoder} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{M} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Park} \\
& \quad \text{Inverse Park} \\
& \quad \text{PI Torque Controller} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Clarke} \\
& \quad \text{Inverse Clarke} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Rotor position - } \theta \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Id} \\
& \quad \text{Iq} \\
\end{align*}
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\[
\begin{align*}
& \quad \text{Vd} \\
& \quad \text{Vq} \\
\end{align*}
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\begin{align*}
& \quad \text{Va} \\
& \quad \text{Vb} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{u, v, w} \\
\end{align*}
\]
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Summary

• Think of a brushless-DC motors like a brushed-DC motor without the brushes
  – Brushed-DC motor: mechanical commutation, brushless-DC motor: electrical commutation

• Sensored versus sensorless
  – Sensored requires additional components but control is easier
  – Sensorless requires fewer components but control is harder
  – Don’t ask to do a sensorless servo

• Comparison of commutation methods (Trap, Sine, FOC)

<table>
<thead>
<tr>
<th></th>
<th>Implementation</th>
<th>Switching Loss</th>
<th>Audible Noise</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap</td>
<td>Easy look-up table</td>
<td>Low</td>
<td>High</td>
<td>Best for high torque or high speed</td>
</tr>
<tr>
<td>Sine</td>
<td>Complex look-up table</td>
<td>High</td>
<td>Low</td>
<td>Not the best for dynamic torque</td>
</tr>
<tr>
<td>FOC</td>
<td>Complex real-time calculation</td>
<td>High</td>
<td>Lowest</td>
<td>Highest efficiency, dynamics</td>
</tr>
</tbody>
</table>
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