Identifying, Analyzing and Mitigating First-, Second- and Third-Order Effects on Motor Control Performance in Vector Control of PMSM Motor Applications

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Agenda

- PMSM vector control
- First-Order Effects
  - Motor parameters
  - Back EMF,
  - Reluctance and Cogging torque
- Second-Order Effects
  - PWM control frequency selection
  - Dead time impact
  - Feedback resolution and sensing
  - Modulation techniques
- Third-Order Effects
  - Fixed point vs. floating point calculations
  - MCU/DSP architecture
- Q & A
PMSM Vector Control

Designers use vector control in PMSM applications to achieve efficiency and performance

- Requires them to trade off many factors and effects
- A balance is required between system level functionality and performance and efficiency

Renesas has many years of experience working with motor control, in particular with vector control

- Many control algorithms have been developed and tested
- Showed how this can influence the MCU/DSC selection criteria

Our experience has shown us that there are many factors to consider when developing and designing for optimum performance and high efficiency

- We have attempted to stratify these considerations into three levels of effects from overall system level down to the MCU/DSC level
Permanent Magnet Synchronous Motor

- Also known as Brushless DC (BLDC) motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Pole</td>
<td>4</td>
</tr>
<tr>
<td>Phase</td>
<td>3</td>
</tr>
<tr>
<td>Voltage</td>
<td>130 V</td>
</tr>
<tr>
<td>Current</td>
<td>1.5 A</td>
</tr>
<tr>
<td>Power</td>
<td>1/5 hp</td>
</tr>
<tr>
<td>Speed</td>
<td>2500 rpm</td>
</tr>
<tr>
<td>Inductance</td>
<td>27 mh</td>
</tr>
<tr>
<td>Stator Resistor</td>
<td>5.1 ohm</td>
</tr>
<tr>
<td>Hall sensors</td>
<td>3</td>
</tr>
</tbody>
</table>

![Motor Diagram]

[Parameter Table]
Vector Control

- Current loop is inside, speed loop is outside
- Sensorless control has flux and position observer
First-Order Effects
First-Order Effects: Parameter Mismatch

- Manifests itself as a gross error in performance
  - E.g., Torque or speed off by 50%, instability, etc.
- A good place to start is the manufacturer’s datasheet or the ratings listed on the nameplate of the motor

Is there a mismatch between what is in the datasheet versus the parameters that are used in the control algorithm?

Are the order of magnitude and units correct?

What is the meaning of specifications and ratings?

Table I. Motor specifications for Bodine 34B series BLDC motor.

<table>
<thead>
<tr>
<th>34B Series BLDC Motor Model 3306 Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
</tr>
<tr>
<td>Category</td>
</tr>
<tr>
<td>Speed (rpm)</td>
</tr>
<tr>
<td>Rated Torque (oz-in)</td>
</tr>
<tr>
<td>Rated Voltage</td>
</tr>
<tr>
<td>Motor HP</td>
</tr>
<tr>
<td>Torque Constant (oz-in/A)</td>
</tr>
<tr>
<td>Voltage Constant (V/krpm)</td>
</tr>
<tr>
<td>Winding Resistance (ohms)</td>
</tr>
<tr>
<td>Winding Inductance (mH)</td>
</tr>
<tr>
<td>Rotor Inertia (oz-in-sec²)</td>
</tr>
<tr>
<td>Radial Load (lbs)</td>
</tr>
<tr>
<td>Length XH (inch)</td>
</tr>
<tr>
<td>Weight (lbs)</td>
</tr>
<tr>
<td>Product Type</td>
</tr>
<tr>
<td>Accessory Shaft</td>
</tr>
<tr>
<td>Connection Diagram</td>
</tr>
</tbody>
</table>
First-Order Effects: Back EMF

- Back EMF is present in all PM Motors
- When the motor rotates, the magnetic field changes, and this induces a voltage that opposes the voltage applied to the motor
  - \( V_a = e_a + R_a \cdot I_a + L_a \cdot \frac{di_a}{dt} \)
  - where \( R_a \) and \( L_a \) are the winding resistance and winding inductance respectively
- The term, \( e_a \), is the Back EMF denoted by
  - \( e_a = k_E \cdot \omega_m \)
  - where \( k_E \) is in units of \( V/(rad/sec) \)
  - Typically specified as \( V/kRPM \) by manufacturers
First-Order Effects: Back EMF Waveform

- Found in manufacturer’s datasheet
- First-order effect is that it limits the top speed of the motor per a given amount of applied voltage because the higher speeds of the motor a larger Back EMF
- At some point, the amount of Back EMF equals the bus voltage, and there is not sufficient voltage that can be applied to the motor to maintain a certain speed
- Can be mitigated to some extent by employing techniques such as space vector modulation
First-Order Effects: Reluctance & Cogging Torques

The **reluctance torque** is the result of differences between the q and d axis inductances in a permanent magnet synchronous motor.

- It manifests itself in the torque performance of the motor.
- Mitigated by employing phase advancing techniques.

The **cogging torque** is created when the magnets in the rotor interact with the slots in the stator.

- Undesirable first-order effect that is apparent when the motor is operating at low speed.
- Mitigated by tuning or employing adaptive feed-forward or current injection techniques.
The motor torque constant, $K_t$, relates the torque produced by the motor with the current through the motor.

- Effective torque constant can be up to 20% lower at peak current than at lower current.
- Mitigate this effect is by properly characterizing $K_t$ as a function of current and temperature. A lookup table can be used to identify $K_t$ and that can be used for the internal model of the motor and control algorithm.
Second-Order Effects
PWM Control Frequency Selection

- Second-order effects are more pronounced in high performance algorithms, such as vector control, and dealt with assuming first-order effects have been satisfied.
- Frequency selection is the result of a tradeoff between performance, efficiency and available CPU bandwidth.
- The test data shown here is from a sensorless vector control algorithm implemented on an RX62N CPU board with a power stage driving a BLDC motor.
- Results show much better control response while maintaining smooth current at the higher PWM freq at the cost of double the CPU bandwidth.
Speed Control @10kHz and 16kHz

Motor Speed Using 10kHz Carrier

- Accuracy is +/- 5 RPM

Motor Speed Using 16kHz Carrier

- Accuracy is +/- 3 RPM

26.5% Bandwidth @10kHz

44.8% Bandwidth @16kHz
Current Control @10kHz and 16kHz

Phase current @10K

Phase current @16K

26.5% Bandwidth @10kHz

44.8% Bandwidth @16kHz
Dead-Time Insertion and Mitigation

- The time inserted between turning OFF the high side and turning ON the low side, or vice versa
  - No power provided to motor during **dead time**
  - Keeps power module from blowing up!
- As a second-order effect, dead time creates a harmonic distortion in the current wave form and injects the disturbance in the current loop affecting the control performance
- Mitigated by simple to complex dead-time compensation techniques to recover performance
- Cost is CPU utilization but tradeoff may be worth it
Dead Time Compensation @10Hz

- Without compensation, current profile has distinct harmonics
- With compensation, current profile is smooth
Dead Time Compensation @30Hz

- Without compensation, current profile has distinct harmonics
- With compensation, current profile is smooth
Feedback Mechanism Resolution

- Digital encoders are commonly used in high-end control where the speed loop is tightly coupled with the current loop.
- Designers must consider the dynamic range, accuracy and speed loop rate that is required when selecting an encoder.
  - Examples given in paper.
- Some designers have a dynamic speed loop where the speed loop rate can change at different speeds.
  - Must consider how loop dynamics and gains change in this case.
Feedback Mechanism Resolution (2)

- The ADC is used for current measurement and is available as a peripheral on an MCU/DSC with 10- or 12-bits resolution.
- 12-bit resolution is better at resolving the zero crossing region and results in better performance.
  - e.g., 10 amp max current per phase at 10-bits resolves 20 mA; has much larger step size than 12-bits which resolves down to 5 mA.
- Can also employ over sampling and filtering to increase resolution of current measurements.
- Be wary of encoder quantization and resolution noise that can back feed into the speed loop.
  - Manifests itself as a torque ripple.
- Can be mitigated by employing fixed speed loop if small counts over speed range are possible or use dynamic loop rate at speed ranges where performance is critical.
Second-Order Effects: Modulation Techniques

- High-end control algorithms typically use sinusoidal methods and their enhancements to continually provide power to all three phases of the motor.

- Input voltage to motor is up to max bus voltage per phase.
- Phase to phase voltage is less due to third harmonic being cancelled as a second-order effect due to the phase voltages shifted 120 degrees apart.
Second-Order Effects: Modulation Techniques

- This second-order effect can be mitigated by injecting the third harmonic back into the phase voltages before it is applied to the motor
  - Known as third harmonic injection or space vector modulation
  - Additional scaling is required

The modified sine modulation has new PWM values which recover the lost phase to phase voltage

- The current value per phase can now achieve the desired maximum value
Third-Order Effects
Third-Order Effects: Fixed-Point vs Floating-Point

- Vector control algorithm requires implementing complex transformations

Vector control is typically implemented in a fixed-point DSP or MCU

Fixed-point implementation has several issues such as saturation, continuous normalization and proper accuracy of the variable being used, especially for the 16-bit DSP devices
Third-Order Effects: Fixed-Point vs Floating-Point

- Renesas implemented both fixed-point and floating-point sensorless vector control algorithms for BLDC motor control.
- Results of comparison were presented at the Motor & Drive 2011 conference.
- Implementation with floating-point uses significantly less code and CPU bandwidth.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed-Point</th>
<th>Floating point</th>
<th>Ratio</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU bandwidth (μsec)</td>
<td>40</td>
<td>26</td>
<td>0.65</td>
<td>FPU 35% better</td>
</tr>
<tr>
<td>Code size (bytes)</td>
<td>13816</td>
<td>7597</td>
<td>0.55</td>
<td>Code reduced by 45%</td>
</tr>
</tbody>
</table>
Third-Order Effects: Processor Core Architecture

- Processor utilization and computational performance are third-order effects that can impact control loop response/performance and ability to perform other tasks
  - Directly influenced by processor architecture and MCU/DSP/DSC selection
- Motor control testing by Renesas is done using a RX62x DSC
- High performance core with enhanced Harvard architecture, 5-stage pipeline, 64-bit wide pre-fetch queue minimizes bottlenecks between CPU and memories
Third-Order Effects: Processor Core Architecture

- Wait state penalty due to slow flash is another third-order effect that impedes processor performance.
- This can be mitigated by selecting a processor that has zero wait states up to the max CPU clock.

- To alleviate CPU burden, take advantage of DMA to automate data transfers such as current measurement.
- RX also has DTC (Data Transfer Controller) peripheral which allows for many more virtual DMA channels.
Third-Order Effects: Synchronized ADC/PWM Triggering

- The designer typically wants to have an automatic triggering of A/D conversion start relative to some point within the PWM timing cycle.
- Having an advanced timer set with double buffering allows for asymmetric PWM and flexibility to set A/D conversion start trigger anywhere on the PWM timing cycle.
- This is especially advantageous when implementing single-shunt sensorless vector control.
- Interrupt skipping capability can allow designer to set up current loop interrupt at a fixed multiple of the PWM frequency to help reduce CPU utilization.

**MTU can generate ADC Start Trigger for Motor Control**
- Two sets of a register for generating trigger and its buffer register built-in
- Can work in conjunction with interrupt skip function
Summary

- Renesas motor control team has shared our experiences within the engineering community
- A summary of first-, second- and third-order effects has been presented
  - First-order effects are system-level effects all designers must satisfy in order to have properly functioning motor control system
  - Second-order effects are pronounced in high-performance motor control implementations such as vector control
  - Identifying and mitigating third-order effects results in a more optimized and robust design
- The RX62T and RX62N DSC are very well suited for dealing with second- and third-order effects
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Thank you