Title: "Motor Control and Regulation for a Flywheel Energy Storage System"

Abstract: This talk will focus on the motor control algorithms used to regulate the flywheel system at the NASA Glenn Research Center. First a discussion of the inner loop torque control technique will be given. It is based on the principle of field orientation and is implemented without a position or speed sensor (sensorless control). Then the outer loop charge and discharge algorithm will be presented. This algorithm controls the acceleration of the flywheel during charging and the deceleration while discharging. The algorithm also allows the flywheel system to regulate the DC bus voltage during the discharge cycle.

Author: Dr. Barbara Kenny received her Ph.D. in electrical engineering from the University of Wisconsin-- Madison in December, 2001. She has a Master's Degree from the University of Texas and a Bachelor's Degree from Cornell University, both in electrical engineering. She has been working at the NASA Glenn Research Center since 1989, first in the area of systems analysis and more recently in motor drives and control. Her current research efforts are focused on developing and demonstrating the technology necessary for a high speed flywheel energy storage system to replace batteries on future spacecraft.
Motor Control and Regulation for a Flywheel Energy Storage System.

Dr. Barbara H. Kenny
11 April 2003

Glenn Research Center
at Lewis Field
Outline of Presentation

- NASA GRC flywheel system
- Control of permanent magnet motor
- Position information feedback techniques
- Flywheel charge & discharge control
- Experimental results
- Conclusions & future work
NASA GRC Flywheel System

- Composite flywheel rim
- Magnetic bearings
- Touchdown bearings
- Motor/generator

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Flywheel System Control Room

• Magnetic Bearing Control

• Motor Control

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Electronics

Flywheel modules

Flywheel test facility

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Flywheel System Motor

- Permanent magnet synchronous machine

2 poles,
3 phase,
65 volts peak,
60,000 rpm
PM Machine Principles of Operation

- Stator
  - 3 phase winding ⇒ rotating magnetic field
  - Effect of 3 phase currents mathematically represented as a current vector on d-q axes

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PM Machine Principles of Operation (II)

- Rotor
  - Permanent magnets provides magnetic field
PM Machine Principles of Operation (III)

- If stator current vector and rotor magnetic field are perpendicular \( \Rightarrow T = 3/2 \ P/2 \ |l_s| \ \lambda_{af} \)
- Current must be properly controlled to maintain 90 degree angle with rotor field.
- Need to know location of rotor field vector, \( \lambda_{af} \), and \( \theta_r \)

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Position Information Feedback Techniques

- Encoder or resolver
  - Mechanical device attached to shaft of machine
  - Speeds are too high for most of these devices
  - Adds length to shaft which reduces maximum speed

\[ \theta_r = 0^\circ \quad \theta_r = 115^\circ \quad \theta_r = 203^\circ \]

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Position Information Feedback Techniques
• Once around signal
  – 1 rising edge per revolution based on optical signal
• Noisy signal, sample rate, start up, alignment

ideal

actual

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Sensorless Position Estimation

- Low speed region
  - Requires "magnetic saliency"
    - $L_q > L_d$
  - Additional high frequency voltage carrier signal, $V_c$, added to fundamental
  - Resulting motor current will contain 3 components:
    - Fundamental: $f_{fund}$
    - "positive sequence": $+f_c$ (~ 3 amps)
    - "negative sequence": $-f_c$ (~ .25 amps)
  - Position information contained in negative sequence component

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Self-Sensing Examples

Phase current with no saliency

Phase current with saliency

Filtered current (ideal)

Proportional to \( \sin(2 \theta) \)

Proportional to \( \cos(2 \theta) \)

Rotor position estimate

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Self-Sensing: Experimental Results

Measured phase current

Filtered current

Rotor position estimate

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“High” Speed Sensorless Control

- Back EMF Technique
  - Faraday’s Law: \( V = \frac{d(\phi)}{dt} \)
  - \( V_{\text{motor}} \propto \frac{d(\lambda_{af})}{dt} \)
  - \( \lambda_{af} \propto \int V_{\text{motor}} \, dt \)
  - Find \( \theta_r \) from components of voltage vector
    - \( \theta_r \propto \tan^{-1} \left( \frac{\int (V_{ds} - i_{ds}R_s) \, dt}{\int (V_{qs} - i_{qs}R_s) \, dt} \right) \)

- Actual motor voltage assumed to be equal to commanded motor voltage; current is measured.

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Back EMF Example

- Commanded motor voltages
- Estimated rotor position

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Rotor Position Estimation Accuracy

- OAR Estimate
- Signal Inj. Estimate
- Bemf Estimate

Relative Errors

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Rotor Position Sensitivity

- Perfect $\theta_r$ estimate $\Rightarrow i_d = 0$
- $\theta_r$ error $\Rightarrow i_d \neq 0$ and $|i_s| \uparrow$

Phase current magnitude

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Block diagram of motor controller

Glen Self-sensing and position and Back EMF position and speed estimation

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NASA
Flywheel Control

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Flywheel Modes of Operation

- Charge
- Charge Reduction
- Discharge

\[
\begin{align*}
I_{s/a} &= I_{load} + I_{*\text{charge}} \\
I_{flywheel} &= I_{*\text{charge}} \\
I_{load} &= I_{flywheel} \\
I_{load} &= -I_{flywheel}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current</th>
<th>DC Bus Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Sun “Charge”</td>
<td>(I_{s/a} = I_{load} + I_{<em>\text{charge}}) (I_{flywheel} = I_{</em>\text{charge}})</td>
<td>Regulated by solar array system</td>
</tr>
<tr>
<td>Partial Sun “Charge Reduction”</td>
<td>(I_{load} + I_{<em>\text{charge}} &gt; I_{s/a} &gt; 0) (I_{</em>\text{charge}} &gt; I_{flywheel})</td>
<td>Regulated by flywheel system</td>
</tr>
<tr>
<td>Eclipse “Discharge”</td>
<td>(I_{load} = -I_{flywheel}) (I_{flywheel} &lt; 0)</td>
<td>Regulated by flywheel system</td>
</tr>
</tbody>
</table>

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Inverter Current Control

- Charge Mode
  \[ I_{\text{inv}} = I_{\text{flywheel}} = I_{\text{charge}} \]

- Discharge Mode
  \[ I_{\text{inv}} \uparrow \text{ causes } V_{\text{dc}} \downarrow \]
  \[ I_{\text{inv}} \downarrow \text{ causes } V_{\text{dc}} \uparrow \]

- \( I_{\text{inv}} \) result of motor operation

How to control motor to achieve desired \( I_{\text{inv}} \)?

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Motor Control Current

- **Field Orientation Control**
  Rotor reference frame
  Control currents DC at steady state
  Motor torque proportional to current

- **Power Balance**
  Mechanical power \( \approx \) electrical power
  \( \omega_r \tau_e \approx P_{\text{elec}} \)
  Average motor electrical power \( \approx \) DC power
  \[
  \frac{3}{2} \frac{P}{2} \lambda_{af} I_{qs} \omega_r \approx \frac{I_{\text{inv}}}{V_{dc}}
  \]
  \[
  i_{qs}^* = \frac{2V_{dc}}{3\omega_r \lambda_{af}}
  \]

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Control Procedure

1. Calculate $\overline{I_{\text{inv}}}^*$
   - Charge mode: regulate charging current
   - Discharge mode: regulate the DC bus voltage
2. Calculate the necessary motor current to achieve $\overline{I_{\text{inv}}}^*$
3. Regulate the motor and motor current through field orientation and a high bandwidth current regulator.
Simulation Results

![Simulation Diagram](image)

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Simulation Results (II)

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Experimental Results (Charge to Discharge)

- Current, amps
- Time, seconds
- Charge reduction to discharge
- Load Current
- ISource
- IFlywheel
- 300 ohms to 120 ohms

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Experimental Results (Charge to Discharge)

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Experimental Results (Discharge to Charge)

- Charge reduction to discharge
- 300 ohms to 120 ohms
- discharge to charge

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Experimental Results (Discharge to Charge)

Gle [300 ohms to 120 ohms] to charge

Load Current

source

flywheel

charge reduction to discharge

<table>
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<tr>
<td>-2</td>
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300 ohms to 120 ohms

discharge to charge

DC bus voltage, volts

| 118 | 120 | 122 | 124 | 126 | 128 |

<table>
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300 ohms to 120 ohms

motor phase current, amp

| -20 | -15 | -10 | -5 | 0 | 5 | 10 | 15 | 20 |

<table>
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300 ohms to 120 ohms

discharge to charge

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Summary and Future Work

• Flywheel energy storage system control demonstrated
  – Sensorless control of permanent magnet machine
    • Low speed signal injection method
    • High speed back EMF method
  – 3 modes of operation: charge, charge reduction and discharge
    • Flywheel system regulates DC bus during discharge
• Multiple flywheel control is next
  – Spacecraft bus regulation, energy storage and attitude control
    • Initial feasibility shown within the last week!

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