Modeling and Digital Control of DC-DC Converters

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Outline

• Introduction
• Digital control – buck converter
• Adaptive sliding mode control – boost converter
• Evaluation of Silicon IGBT vs. SiC MOSFET for a buck converter
• Test and comparison
• Summary
Introduction

• DC-DC converters play a critical role in the energy conversion
• Design and component selection
  • Circuit and controller design
  • Component selection
  • Selection of switching frequency
  • Loss estimation

DC-DC Converters

• EMC analysis
  • Analyze electromagnetic interference
  • Determination of switching transients
  • Optimal circuit layout to minimize parasitics
• Mechanical and thermal design
  • Thermal management
  • Packaging
Introduction (cont’d)

• The Advanced Photon Source (APS) at Argonne National Laboratory is a premier national research facility

• It provides the brightest x-ray beams in the Western Hemisphere to more than 5,000 scientists from the U.S. and around the world

DC-DC Converters

• In order to develop the photon sources, a beam of high energy electrons are guided through a storage ring using powerful magnets

• Currently more than 1,300 DC-DC converters are used
  • 15+ years old
  • Analog control
DC-DC Converters

• The APS upgrade for 2020 may increase to nearly 3,000 DC-DC converters

• These power supplies require high resolution for output current regulation, and high reliability

• Digital upgrade
  • Higher reliability
  • Less susceptible to aging and environmental variations

• Intelligence
  • Monitoring
  • Self-diagnostics
  • Communication to a host computer

Buck Converter

• Long time constant
  • Filter not needed

• Small signal analysis performed
Buck Converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage $V_{in}$</td>
<td>62</td>
<td>V</td>
</tr>
<tr>
<td>Maximum output current</td>
<td>250</td>
<td>A</td>
</tr>
<tr>
<td>Magnet inductance $L_m$</td>
<td>28</td>
<td>mH</td>
</tr>
<tr>
<td>Magnet series resistance $R_m$</td>
<td>110</td>
<td>mΩ</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20</td>
<td>kHz</td>
</tr>
</tbody>
</table>

Small Signal Model

- Current to be controlled
- Current variations due to duty cycle

$$G_{id} = \frac{\hat{i}(s)}{d(s)} = \frac{V_{in} - \left(\frac{V_{in}d_0}{R_m}\right)R_{on} + V_f}{sL_m + (d_0R_{on} + R_m)}$$

- Current variations due to source voltage

$$G_{iv} = \frac{\hat{i}(s)}{\hat{v}(s)} = \frac{d_0}{sL_m + (d_0R_{on} + R_m)}$$

- Superposition

$$\hat{i}(s) = G_{id}\hat{d}(s) + G_{iv}\hat{v}(s)$$
Design Requirements

- Low current variations
  - 1 mA out of 250 A
- No overshoot
- Switch between two controls
  - Control I – Faster response
  - Control II – Slower with no overshoot

PI Controller I

- PI compensator
  \[ G_{c1}(s) = 0.007 + \frac{0.0259}{s} \]
- System dynamics
  - Phase margin 90.8°
  - Bandwidth 15.6 rad/s
- Digital Implementation (ZOH)
  \[ G_{c1}(z) = \frac{0.007z - 0.006999}{z - 1} \]
PI Controller II

• PI compensator
  \[ G_{c2}(s) = 0.0035 + \frac{0.01295}{s} \]

• System dynamics
  • Phase margin 91.4°,
  • Bandwidth 7.66 rad/s

• Digital Implementation (ZOH)
  \[ G_{c2}(z) = \frac{0.0035z - 0.003499}{z - 1} \]

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Noise in Output Current

• Prototype converter implementation
• Undesirable noise observed
FFT Analysis of Noise

- Frequency components
  - 360 Hz, 720 Hz, 20 kHz

Analysis of Noises

- Coupled through current sensor
- Circuit techniques used
  - Grounding
  - Shielding
- Filter required
Filter Design

- Pass band
  - 100 Hz
  - 0.1 db
- Stop band
  - 300 Hz
  - 65 db
- Filter has little effect on system
  - System bandwidth about 2.5 Hz

Results of Filtering

- Noise signals considerably reduced
Comparison of Different Types of Digital Filters

<table>
<thead>
<tr>
<th></th>
<th>Butterworth</th>
<th>Chebyshev -I</th>
<th>Chebyshev -II</th>
<th>Elliptic</th>
<th>Maximally Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop band attenuation (dB)</td>
<td>69.5</td>
<td>69.5</td>
<td>69.5</td>
<td>78.28</td>
<td>49</td>
</tr>
<tr>
<td>Filter order</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Multiplication</td>
<td>18</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Addition</td>
<td>18</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Delay</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Step Response of Digital Simulation using Different Filters

![Step response diagram](image)
Voltage Feedforward Control

- Input voltage variations create disturbances
- Duty cycle adjusted
  - Based on variation from nominal voltage

\[ d' = \frac{V_{in}'}{V_{in}} \times d \]

- \( V_{in} \) = nominal voltage
- \( V_{in}' \) = actual voltage
- \( d \) = nominal duty cycle
- \( d' \) = actual duty cycle

System Block Diagram

- Simplified diagram
Simulation Results

- Fast rise at startup transient
- No overshoot
Digital Control – Buck Converter

• Summary
  • A digital control system has been designed and evaluated for buck converters at the Advanced Photon Source at the Argonne National Lab
  • PI controllers were designed for the converter using frequency response techniques
  • A digital controller can easily switch between two sets of gains based on the output current error
    • First set of PI controller: fast transient response
    • Second set of PI controller: better steady state response

Adaptive Sliding Mode Control – Boost Converter

Boost converter
Averaged Model of Boost Converter

\[
\begin{align*}
\dot{x}_1 &= -(1-u) \frac{x_2}{L} + \frac{V_o}{L} \\
\dot{x}_2 &= -(1-u) \frac{x_1}{C} - \frac{\theta}{C} x_2
\end{align*}
\]

- \(x_1\) – Average inductor current \(i_L\)
- \(x_2\) – Average capacitor voltage \(v_o\)
- \(L\) – Inductor
- \(C\) – Capacitor
- \(R_O\) – Load resistor
- \(\theta\) – 1/\(R_O\)
- \(V_{in}\) – Input voltage

Control for Boost Converter

- Boost converter’s model is nonlinear
- Inherently variable structured because of the switching action
- Sliding mode control
  - A systematic design method
    - Can yield a closed loop system that is very robust against plant uncertainties and external disturbances
- PWM-based adaptive sliding mode control
Sliding Mode Control

\[ \dot{x}_1 = -(1-u) \frac{\bar{x}_1}{L} + \frac{\bar{V}}{L} - K_1 \bar{x}_1 \]
\[ \dot{x}_2 = -(1-u) \frac{\bar{x}_2}{C} - \frac{\hat{\theta}}{C} x_2 - K_2 \bar{x}_2 \]

Where
- \( \hat{\theta} \) and \( \hat{V}_m \) are the estimates of \( \theta \) and \( V_m \) respectively
- \( \dot{x}_1 \) and \( \dot{x}_2 \) are the estimates of \( x_1 \) and \( x_2 \) respectively
- \( K_1 > 0 \) and \( K_2 > 0 \) are the observer gains
- \( \bar{x}_1 = x_1 - \hat{x}_1, \bar{x}_2 = x_2 - \hat{x}_2, \bar{\theta} = \theta - \hat{\theta}, \bar{V}_m = V_m - \hat{V}_m \)

Estimator-Based Adaptation Laws Design
Adaptation Law

- To generate the adaptation laws, we consider the following Lyapunov function
  \[ V = \frac{1}{2} L \ddot{x}_1^2 + \frac{1}{2} C \dddot{x}_2^2 + \frac{1}{2\gamma_1} \ddot{\theta}^2 + \frac{1}{2\gamma_2} \dddot{\theta}^2 \]

- Time derivative along the Lyapunov function
  \[ \dot{V} = -K_1 L \ddot{x}_1^2 - K_2 C \dddot{x}_2^2 - \dddot{\theta} \left( x_2 \dddot{x}_2 + \frac{1}{\gamma_1} \ddot{\theta} + \dddot{\theta} \right) + \dddot{\theta} \left( \ddot{x}_1 - \gamma_2 \dddot{\theta} \right) \]

- Adaptation law
  \begin{align*}
  \ddot{\theta} &= -\gamma_1 x_2 \dddot{x}_2 \\
  \dddot{\theta} &= \gamma_2 \dddot{x}_1
  \end{align*}

Sliding Mode Controller Design

- Switching surface
  \[ \sigma = \hat{x}_1 - \frac{V_{\text{ref}}^2}{V_{in}} \hat{\theta} \]

- Control is derived by differentiating \( \sigma \) with time
  \[ u_{\text{eq}} = 1 - \frac{(\dddot{\dot{x}}_1 + K_1 L \ddot{x}_1 + \frac{\gamma_1}{V_{\text{ref}}^2} x_2 \dddot{x}_2 + \frac{\gamma_2 L}{V_{\text{ref}}^2} \dddot{\theta})}{\dddot{x}_2} \]
Adaptive Sliding Mode Control System

![Adaptive Sliding Mode Control System diagram]

Boost Converter

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<tr>
<td>Input voltage $V_{in}$</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>Inductance L</td>
<td>180</td>
<td>μH</td>
</tr>
<tr>
<td>Capacitance C</td>
<td>150</td>
<td>μF</td>
</tr>
<tr>
<td>Output resistance</td>
<td>40</td>
<td>Ω</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>200</td>
<td>kHz</td>
</tr>
</tbody>
</table>
Transient Response with Step Reference Voltage Change – $V_{\text{ref}}$ from 7 V to 12 V

Output voltage
Sliding surface
Inductor current

Sept 24, 2015
IEEE Rock River Valley Section Meeting

Transient Response with the Load Resistor $R_o$
Varying Between 40 Ω and 160 Ω

Output voltage
Sliding surface
Inductor current

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Transient Response with the Input Voltage $V_{in}$ Varying From Nominal Value of 6 V to 10 V

Output voltage

Sliding surface

Inductor current

Adaptive Sliding Mode Control – Boost Converter

• Summary
  • Controller were designed to deal with unknown load resistance and input voltage
  • Closed-loop system is asymptotically stable
  • Experimental results show excellent recovery to input voltage variations and unmodelled load variations
  • The controller design can be easily extended to other DC-DC converters
Wide Band Gap (WBG) Devices

- Main advantages of WBG devices
  - Much smaller switching losses
  - Able to operate at higher temperature without much change in electrical properties, leading to better reliability
  - High frequency of operation, leading to smaller passive components
  - Allow power electronics components to be smaller, faster, more reliable and efficient

Modeling of SiC MOSFET

- A level-1 SPICE model for the 1,200 V / 100 A half-bridge SiC power MOSFET module was developed
- Circuit model parameters for the SiC MOSFET were extracted from the measured static I-V and C-V data.
- A double pulse gate switching circuit was used to validate the model
Key Device Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Silicon IGBT</th>
<th>SiC MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Rating (V)</td>
<td>600</td>
<td>1,200</td>
</tr>
<tr>
<td>Current Rating (A) @ T&lt;sub&gt;j&lt;/sub&gt; = 25°C</td>
<td>400</td>
<td>168</td>
</tr>
<tr>
<td>Forward voltage drop (V) @ T&lt;sub&gt;j&lt;/sub&gt; = 25°C and V&lt;sub&gt;GE&lt;/sub&gt; = 15V</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>On resistance (mΩ)</td>
<td>16 @ T&lt;sub&gt;j&lt;/sub&gt; = 25°C and V&lt;sub&gt;GS&lt;/sub&gt; = 20V</td>
<td>41</td>
</tr>
</tbody>
</table>

Tests #1 – Conduction Losses

- Computation of the conduction and switching losses at 20 kHz when the load current varies from 50 A to 400 A.
Test #1 – Switching Losses

![Graph showing Switching Losses for IGBT and MOSFET](image)

Test #2

- Computation of the conduction and switching losses for 4 different loads as the switching frequency is varied from 5 kHz to 25 kHz
  - 100 A, 200 A, 300 A, 400 A
Test #3

- Varying the switching frequency of the SiC MOSFET to a wider range from 30 kHz to 150 kHz
Conclusion

- Buck converter
  - PI controller with two sets of gains
  - Digital filter

- Boost converter
  - Adaptive sliding mode control

- SiC power MOSFET based dc-dc converters have the potential for significant improvement in the energy efficiency compared to silicon IGBT converters currently employed