Lecture-36

EE5325 Power Management Integrated Circuits

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Buck-Boost Converter
Types of DC-DC converter

**BUCK:** \( \frac{V_{\text{out}}}{V_{\text{in}}} < 1 \)

\( V_{\text{out}} = D V_{\text{in}} \), \( I_L = I_o \)

**BOOST:** \( \frac{V_{\text{out}}}{V_{\text{in}}} > 1 \)

\( V_{\text{out}} = \frac{1}{1-D} V_{\text{in}} \), \( I_L = \frac{1}{1-D} I_o \)

**BUCK-BOOST:** \( \frac{V_{\text{out}}}{V_{\text{in}}} \approx 1 \)

\( V_{\text{out}} = D \frac{V_{\text{in}}}{1-D} \), \( I_L = \frac{1}{1-D} I_o \)

Also works as buck only or boost only
Why Buck-Boost?

- Considering the Li-ion battery discharge profile, either buck or boost fails to operate for the output voltage of 3.3V - 3.6V
  - Converter needs to be operated in buck-boost mode for most of the time
Drawback of Conventional BB converter

- Single Duty cycle, D, controls all the switches.
- Switching losses are higher due to simultaneous operation of 4 switches
- Conduction losses are higher due to larger Inductor current (nearly 2x when Vin \( \approx \) Vout.)

\[
V_{out} = \frac{D}{1-D} V_{in} \quad (1)
\]
\[
I_L = \frac{1}{1-D} I_o \quad (2)
\]
Tri-Mode Operation of BB Converter

- $V_{IN} > V_{OUT}$: Buck Mode
- $V_{IN} < V_{OUT}$: Boost Mode
- $V_{IN} \sim V_{OUT}$: Buck-Boost Mode
## Conventional vs. Tri-Mode Efficiency

Input Voltage $V_{in} = 2.7V$ to $5.5V$, $V_{out} = 3.3V$, $I_{load} = 500mA$

<table>
<thead>
<tr>
<th>Input Voltage $V_{in}$ $[V]$</th>
<th>Proposed Buck-Boost (Measured)</th>
<th>Conventional Buck-Boost (Simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing efficiency comparison between Tri-Mode Buck Boost and Conventional Buck Boost](image)

- **Tri-Mode Buck Boost**
- **Conventional Buck Boost**
Tri-Mode: Buck

Increasing $V_{IN}$

- **Buck**
- Buck-Boost
- **Boost**

$V_{OUT}$

- $P_{BO}$ always ON
- $D_{BUCK}$ controls buck switches

$V_{OUT} \approx (D_{BUCK})V_{IN}$

$I_L = I_{LOAD}$
Tri-Mode: Boost

- \( P_{BU} \) always ON
- \( D_{BOOST} \) controls boost switches

\[
V_{OUT} \approx \frac{V_{IN}}{1 - D_{BOOST}}
\]

\[
I_L = \frac{I_{LOAD}}{1 - D_{BOOST}}
\]
Tri-Mode: Buck-Boost

- $D_{BUCK}$ controls buck switches
- $D_{BOOST}$ controls boost switches

\[
V_{OUT} \approx \frac{D_{BUCK}}{(1 - D_{BOOST})} V_{IN}
\]
\[
I_L = \frac{I_{LOAD}}{1 - D_{BOOST}}
\]
Issue with Tri-Mode Buck-Boost

- Mode transition causes large voltage transient
- Boundary condition must be satisfied
  - Varies with load current and losses

Li-ion battery discharge curve

\[ V_{\text{OUT}} \approx \frac{D_{\text{BUCK}}}{(1 - D_{\text{BOOST}})} V_{\text{IN}} = \frac{0.9}{(1 - 0.1)} \times 3.7 = 3.7 \text{V} \]

Buck Mode: \( D_{\text{BOOST}} = 0 \)
Boost Mode: \( D_{\text{BUCK}} = 1 \)

Boundary Condition

\[ V_{\text{OUT}} (\text{buck}) = V_{\text{OUT}} (\text{buck} - \text{boost}) \]
\[ D_{\text{BUCK}_{\text{max}}} = \frac{D_{\text{BUCK}}}{1 - D_{\text{BOOST}_{\text{min}}}} \]
\[ D_{\text{BUCK}} = D_{\text{BUCK}_{\text{max}}} \times (1 - D_{\text{BOOST}_{\text{min}}}) \]

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Solutions for Mode Transitions

- Appropriate Feed-forward voltage $v_f1 - 4$ is subtracted to instantaneously change the duty cycles during mode transition.

- Analog Implementation makes it susceptible to PVT and requires external compensation capacitor

Digital Constant ON/OFF Time Buck-Boost Converter

- Uses constant ON/OFF technique
- Enables High Switching Frequency Operation
- All digital implementation eliminates the need of external compensation capacitor

Constant ON/OFF Time Operation

Inductor ripple current, \( \Delta I_L = \frac{V_{IN} - V_{OUT}}{L} T_{ON} \) (1)

\[ T_{ON} = D \cdot T \quad T_{OFF} = (1 - D) \cdot T \]

- Max ripple occurs at \( D=0.5 \) (\( Ton = Toff \))
  - The converter can be operated at high switching frequency when \( D=0.5 \)
- From eq. 1, \( D \) increases with \( Vin \)
  - Fixing OFF time and making ON time function of \( Vin \) does not affect the inductor ripple
  - Causes variable switching frequency

<table>
<thead>
<tr>
<th>Time/uSecs</th>
<th>Vout [V]</th>
<th>ΔIL [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>800.05</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.1</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.15</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.2</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.25</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.3</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.35</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.4</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.45</td>
<td>3.34</td>
<td>-60</td>
</tr>
<tr>
<td>800.5</td>
<td>3.34</td>
<td>-60</td>
</tr>
</tbody>
</table>

- \( Ton=137nS \) \( Vin=4.5V \)
- \( Ton=97nS \) \( Vin=5.0V \)
- \( Ton=75nS \) \( Vin=5.5V \)
- \( Toff=constant=50nS \)
Fractional-N Control

Buck Mode:
N cycles of 50% Buck : 1 cycle of 100% Buck

Buck-Boost Mode:
1 cycle of 50% Buck : 1 cycle of 50% Boost

Boost Mode:
N cycle of 50% Boost : 1 cycle of 0% Boost
Fractional-N Control Logic

- Predefined states are stored in the lookup table providing the coarse voltages
- Uses 18-bit acc for integrating the error (4 MSBs, 7 LSBs, 7 dropped bits.
- Any intermediate states are resolved by ΔΣ Modulator

<table>
<thead>
<tr>
<th>Operating States</th>
<th>Control Code</th>
<th>Fraction N:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST1</td>
<td>0001</td>
<td>50%Buck:100%Buck 5:1</td>
</tr>
<tr>
<td>ST2</td>
<td>0010</td>
<td>4:1</td>
</tr>
<tr>
<td>ST3</td>
<td>0011</td>
<td>3:1</td>
</tr>
<tr>
<td>ST4</td>
<td>0100</td>
<td>2:1</td>
</tr>
<tr>
<td>ST5</td>
<td>0101</td>
<td>1:1</td>
</tr>
<tr>
<td>ST6</td>
<td>0110</td>
<td>50%Buck:50%Boost 1:1</td>
</tr>
<tr>
<td>ST7</td>
<td>0111</td>
<td>50%Boost:0%Boost 1:1</td>
</tr>
<tr>
<td>ST8</td>
<td>1000</td>
<td>2:1</td>
</tr>
<tr>
<td>ST9</td>
<td>1001</td>
<td>3:1</td>
</tr>
<tr>
<td>ST10</td>
<td>1010</td>
<td>4:1</td>
</tr>
<tr>
<td>ST11</td>
<td>1011</td>
<td>5:1</td>
</tr>
</tbody>
</table>

Buck Mode

Buck-Boost Mode

Boost Mode

Decreasing VIN

5.5V

2.7V

Predefined states are stored in the lookup table providing the coarse voltages.
Start-up Control

- Startup time is the function of no. of bits dropped in the accumulator and converter resolution

- No. of ACC bits dropped = 7
  → The startup time may be more than 10ms

- Speeded up by dropping only 3 bits in accumulator and switch to 7 bits once the output settles
Inductor Current Profile

ST1: ΔIL = 340 mA

ST2: ΔIL = 314 mA

ST4: ΔIL = 240 mA

ST5: ΔIL = 165 mA
Controller Response

Settled LSB Code

Dithered Output (Control Code)

Comp Out[V]

MSB Code

DSM+MSB

Comp Out[V]

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Output Voltage Ripple

Buck Mode (Vin=5V)

Buck-Boost Mode (Vin=3.6V)

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Mode Transition

- **V\_OUT [V]**
  - Buck
  - Buck-boost

- **IL [A]**
  - Buck
  - Buck-boost

- **D\_BOOST [V]**
  - Buck
  - Buck-boost

- **D\_BUCK [V]**
  - Buck
  - Buck-boost
Hybrid PWM Fractional-N Control

<table>
<thead>
<tr>
<th>Buck Mode</th>
<th>Buck-Boost Mode (Fractional-N)</th>
<th>Boost Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DBOOST = 0</td>
<td>DBOOST = VPWM</td>
</tr>
<tr>
<td></td>
<td>DBUCK = VPWM</td>
<td>DBUCK = 1</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{Vc}_\text{min} &= 0.1 \text{Vm} \\
\text{Vc}_\text{max} &= 0.9 \text{Vm}
\end{align*}
\]