Prototype Implementation of a High Efficiency, Soft Switching DC-DC Converter with Adaptive Current-Ripple Control

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April 19, 2004
Motivation

**Motivation for Improving Efficiency in Mobile Applications**

- Portable application → Compact, low power, low cost, SOC
- Process technology advancement → Low voltage circuits
  - Single battery operation
- Extension of battery life → Highly power efficient DC-DC converter

**Research Goal**

Improve *power efficiency* of integrated DC-DC converters to *extend battery life* for *portable, battery-powered* applications.
Evaluation of Battery Life

**Battery Life**

\[
\text{Battery Life [h]} = \frac{\text{Battery Capacity [mAh]}}{\text{Total Average (Weighted) Battery Current [mA]}}
\]

**Total Average (Weighted) Battery Current, \(I_{\text{Batt Avg Tot}}\)**

\[
\eta(I_{\text{load}}) = \frac{V_{\text{out}} \times I_{\text{load}}}{V_{\text{Batt}} \times I_{\text{Batt}}} \quad \Rightarrow \quad I_{\text{Batt}}(I_{\text{load}}) = \left( \frac{V_{\text{out}}}{V_{\text{Batt}}} \right) \frac{I_{\text{load}}}{\eta(I_{\text{load}})}
\]

\[
I_{\text{Batt Avg Tot}} = \int_{0}^{I_{\text{load max}}} \left[ \text{PDF}(I_{\text{load}}) \times I_{\text{Batt}}(I_{\text{load}}) \right] dI_{\text{load}} = \sum_{i} \text{Probability}(I_{\text{load}}) \times I_{\text{Batt}}(I_{\text{load}})
\]

Charge (Energy) drawn from the battery

**Conclusion**

- Battery life is highly dependent on the probability distribution (PDF) of the load.
- Improve power efficiency at the load current where the most charge / energy is drawn from the battery, i.e., \((\text{Probability} \times I_{\text{Batt}})\) is the largest.
Adaptive Current Ripple Control

• Idea

Soft switching + Reduce current ripple to optimize the efficiency!

• Operation Modes

- High loads (region I): Constant current ripple, hard switching

- Moderate and light loads (region II & III):
  Adaptive ripple, Soft switching

- Very light loads (region IV):
  Constant peak current, hard switching (Burst Mode)
Effect of Power MOSFET Size

• Characteristics of Power MOSFET

<table>
<thead>
<tr>
<th></th>
<th>ON-Resistance</th>
<th>Input Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conduction Loss</td>
<td>Switching Loss</td>
</tr>
<tr>
<td>Big FET</td>
<td>Small</td>
<td>Big</td>
</tr>
<tr>
<td>(e.g. IRF 7309)</td>
<td>(e.g. 80 mΩ at 4.5V)</td>
<td>(e.g. 520 pF)</td>
</tr>
<tr>
<td>Small FET</td>
<td>Big</td>
<td>Small</td>
</tr>
<tr>
<td>(e.g. IRF 7105)</td>
<td>(e.g. 160 mΩ at 4.5V)</td>
<td>(e.g. 330 pF)</td>
</tr>
</tbody>
</table>

• Conclusions

- At *high loads* ➔ Conduction losses dominate ➔ Use *big FET*
- At *light loads* ➔ Switching losses dominate ➔ Use *small FET*
- If power MOSFETs are integrated ➔ *Dynamic Gate Sizing*
Prototype Implementation

• Top Level Schematic

• Comments
  - Assuming output voltage is ESR dominant, voltage-mode hysteretic control is used to adaptively regulate the inductor current ripple.
  - Hysteresis is manually adjusted for the minimum current ripple needed for soft switching.
Experimental Results – Power Efficiency

- **Converter Parameters**
  
  \[ V_{\text{in}} = 5V, \ V_{\text{out}} = 1.8V, \ 0 < I_{\text{load}} < 1A \]
  
  \[ L_f = 8.2 \ \mu \text{H} \ (20 \ \text{m}\Omega \ \text{ESR}), \ C_f = 47 \ \mu \text{F} \ (75 \ \text{m}\Omega \ \text{ESR}), \ C_r = 4.5 \ \text{nF} \]

- **Efficiency Performance**

  ![Graph showing efficiency performance for different FET types and control modes.](attachment:image.png)

  - Big FET, Soft, Adaptive ripple
  - Big FET, Hard, Constant ripple
  - Small FET, Soft, Adaptive ripple
  - Small FET, Burst Mode

  **Parameters**:
  
  \[ V_{\text{in}} = 5V, \ V_{\text{out}} = 1.8V, \ 0 < I_{\text{load}} < 1A \]
  
  \[ L_f = 8.2 \ \mu \text{H} \ (20 \ \text{m}\Omega \ \text{ESR}), \ C_f = 47 \ \mu \text{F} \ (75 \ \text{m}\Omega \ \text{ESR}), \ C_r = 4.5 \ \text{nF} \]
Experimental Results – Battery Life

- **Stress Test Setup**

- **Load Probability**

  For DSP, µProcessor Application

<table>
<thead>
<tr>
<th>I_{load} (mA)</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob (%)</td>
<td>90</td>
<td>4</td>
<td>3</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Product</td>
<td>9</td>
<td>4</td>
<td>30</td>
<td>250</td>
<td>150</td>
</tr>
</tbody>
</table>

- **Results**

  - Improve efficiency at 100 mA, not 100 µA, to prolong battery life!
  - 6 % improvement in battery life
Experimental Results – Other Performance

- **Switching Frequency and Current Ripple**
  - **Switching Frequency Comparison**
  - **Current Ripple Comparison**

- **Transient Response**

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Conclusion and Future Work

• **Conclusion:**
  - Improve the power efficiency at the load current where the most charge / energy is drawn from the battery, which may not be the highest probability load.
  - Adaptive current ripple control in DCM soft switching improves the power efficiency at light and moderate load currents, which significantly increases the battery life.
  - Using small power MOSFET at light loads further reduces the switching loss, therefore dynamic gate sizing is beneficial in the integrated solution.

• **Future Work:**
  - Investigate how to sense the load current to automatically adjust the hysteresis.
  - Investigate how to determine the mode transition points automatically.
  - Investigate how to implement the control strategy with ceramic output capacitors.
  - Implement the whole system in an integrated circuit.