Inductorless DC-DC Converters for Portable Applications - Reality or Fantasy?

Aditya Makharia
Advisor: Prof. Gabriel A Rincón- Mora

Georgia Tech Analog Consortium
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, USA

March 21, 2003
Abstract

Mobile, battery-powered applications require:
» Low Voltage, High Efficiency, High Power, High Accuracy solutions.
» SOC ➔ Integrated Power Supply circuits (dc-dc) ➔ Integrated Power Inductors

DC-DC converters use discrete inductors, which:
» Impede SOC Implementation ➔ Take-up PCB Real Estate ➔ Add Cost

Inductorless versions currently available are:
» Charge Pumps (use off-chip capacitors) ➔ suitable only for low power Apps.
» Linear Regulators – suffer from poor efficiency.

Goal:
» Design a fully integrated DC-DC Converter for Portable Power Applications.
» Integrate Power Inductors on to the die (IC).
Maximize the use of integrated inductors through circuit level techniques, like Inductor Multipliers, as well as through fabrication process steps.
Role of Inductors in Power Supply Ckts.

Buck (Step-down) DC-DC Converter

- Transfers energy from input to output in a lossless fashion.
- Filters the output from switching signals.

Inductor determines output current ripple ($\Delta I_L$), voltage ripple ($\Delta V_o$), and bandwidth requirements.

$$\Delta I_L = \left(\frac{V_{IN} - V_O}{L}\right)_{on}$$

$$\Delta V_o = \left(\frac{V_{IN} - V_O}{L}\right)_{on} \cdot R_{ESR\_C}$$

3 complex poles @ $\frac{1}{2\pi\sqrt{LC}}$

As $L \downarrow$  $\Delta I_L \uparrow$  $\Rightarrow$  Power $\uparrow$, $V_{O\_Ripple} \uparrow$  $\Rightarrow$  Accuracy $\downarrow$
Inductorless Options

• **Switched-Capacitor/Charge Pumps:**
  Capacitor are used for transferring energy.
  
  **Operation:**
  Periodic charging and discharging of capacitors, from the supply to the load.

  **Pros:**
  - Inductorless

  **Cons:**
  - Limited output current
  - Use of off-chip capacitors (large capacitors required even for low load currents)

**Switched-capacitor voltage doubler**

• **Linear Regulators:**
  Only a switch (resistor) is used for transferring energy.

  **Operation:**
  Value of resistance is modulated by feedback control of the output voltage.

  **Pros:**
  - Simple and low cost
  - Inductorless and capable of full integration (<1A application).

  **Cons:**
  - Low efficiency - resistors are lossy!

**Typical Linear Regulator**

**Conclusion:** Good only for low-power applications.
• MEMS Approach:
  Use of MEMS technology to fabricate on-chip inductors

Micromachined Inductor

• Pros:
  - Fully Integrated
  - Relative low cost processing (does not require state-of-the-art technologies)

• Cons:
  - Poor inductor Q factor → Low Efficiency
  - Process compatibility with current main stream fabrication processes → Cost for products ↑
  - Reliability ?

**Conclusion: Yet to be effective!**

---

**New Possible Approach**

**Inductor Multiplier - Voltage-mode:**
» Maximize the value of inductor by decreasing voltage across it.

**Operation:**
» Given the same \( \frac{di}{dt} \) the voltage is decreased to have higher effective inductance

\[
V = L \frac{di}{dt} = L(K \frac{di}{dt}) \Rightarrow K \times L \frac{di}{dt} \quad \therefore \text{Leff} = K \times L
\]

**Implementation:**
» Use a current-controlled-current-source to sense the ripple current through the inductor and multiply it

**Feasibility:**
» Scaling down \( V_{IN} \) will result in increased losses, across A and B and hence poor efficiency.
» The direction of output current works against getting \( V_{OUT\_EFF} < V_{OUT} \) as it requires B to have negative resistance
New Possible Approach

- **Inductor Multiplier - Current-mode:**
  » Sense the current, multiply it, and apply back to the node

- **Operation:**
  » The voltage across the inductor is constant therefore to enhance the value of inductor, current is multiplied.

\[ V = L \frac{di}{dt} = L(K \frac{di}{dt}) \Rightarrow K \times L \frac{di}{dt} \therefore \text{Leff} = K \times L \]

- **Implementation:**
  » Use a current-controlled-current-source to sense the ripple current through the inductor and multiply it

- **Feasibility:**
  The potential at node A is greater than B, hence the flow of current is not realizable. Since A is a low-impedence node, take the current to ground. This realization leads to increased losses.
Simulation Results

Buck converter with current mode inductor multiplier

Output Voltage with/without multiplier

The voltage ripple using 150nH inductor is reduced 10 times with current-mode inductor multiplier technique, and equals the performance with 1.5uH inductor.

The worst case efficiency of the buck converter with inductor multiplier was found to be 76%.
### Comparative Evaluation

<table>
<thead>
<tr>
<th></th>
<th>Charge Pumps</th>
<th>External Inductor</th>
<th>Linear Regulators</th>
<th>MEMS Approach</th>
<th>Inductor Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>**SOC Feasibility *</td>
<td>Worst</td>
<td>Worst</td>
<td>Better</td>
<td>Good</td>
<td><strong>Best</strong></td>
</tr>
<tr>
<td><strong>Output Power</strong></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td><strong>Cost (PCB Estate)</strong></td>
<td>High</td>
<td>Highest</td>
<td><strong>Lowest</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Good</td>
<td>Best</td>
<td>Worst</td>
<td>Poor</td>
<td><strong>Average</strong></td>
</tr>
</tbody>
</table>

* Except $C_{OUT}$

- Inductor multiplier enables complete integration of dc-dc converters for medium power portable applications.
- The implementation also benefits from lower cost but gets a hit on efficiency.
Conclusions and Future Work

• Next generation portable applications demand completely integrated power-management circuits (dc-dc converters).

• Present fabrication processes do not allow integration of high quality inductors for power management applications.

• Inductorless options like linear regulators and charge pumps, suffer from poor efficiency and output power handling capacity respectively.

• Integration of inductors through micromachining techniques has yet to prove effective.

• One approach could be to realize smaller inductors on chip and maximize its effect with inductor multiplier.

• Step-down converter with current-mode inductor multiplier gives the same voltage ripple (accuracy) performance as with an inductor of higher value.

• Power losses are increased with inductor multiplier, but it still provides better efficiency than linear regulators and is a cost-effective fully integrated medium power solution.

• Investigate fabrication of inductors using System-on-Package techniques.