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

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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***

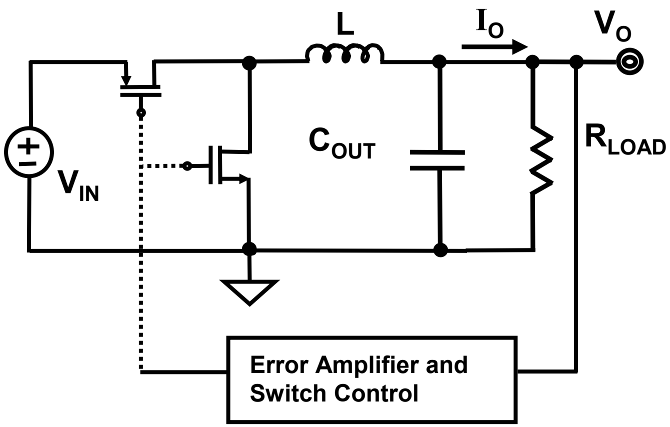
- **Inductorless versions currently available are:**
  - » Charge Pumps (use ***off-chip*** capacitors) ➔ suitable only for ***low power*** Apps.
  - » Linear Regulators – suffer from poor ***efficiency.***

- **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



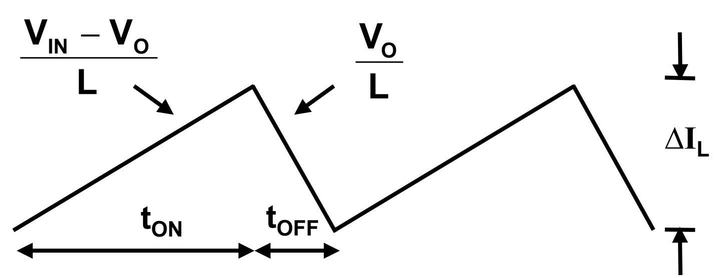
- Transfers energy from input to output in a lossless fashion.
- Filters the output from switching signals.

- Inductor determines output current ripple (ΔI_L)[1], voltage ripple (ΔV_O)[2], and bandwidth requirements[3].

$$^1\Delta I_L = \left(\frac{V_{IN} - V_O}{L}\right) t_{on} \qquad ^2\Delta V_o = \left(\frac{V_{IN} - V_O}{L}\right) t_{on} * R_{ESR\_C}$$

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

Inductor Current in Buck Converter

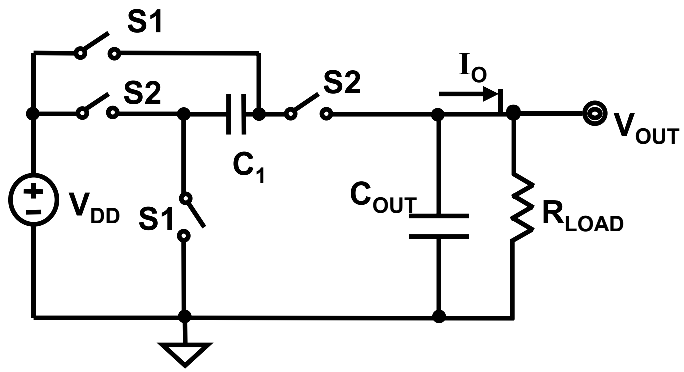


As L ↓ ⇒ ΔI_L ↑ ⇒ Power ↑ , V_{O_Ripple} ↑ ⇒ Accuracy ↓

Inductorless Options

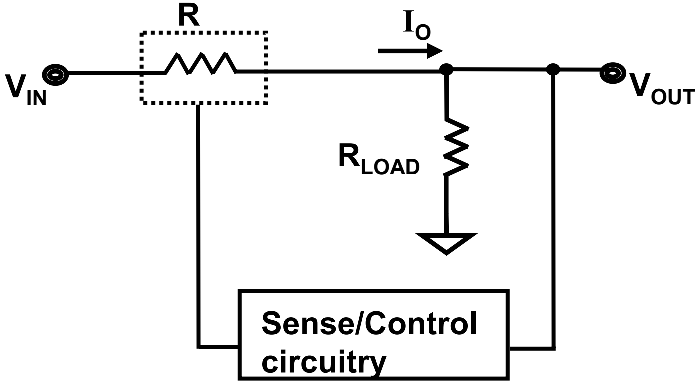
- **Switched-Capacitor/Charge Pumps:**
  Capacitor are used for transferring energy.
- **Operation:**
  Periodic charging and discharging of capacitors, from the supply to the load.
- **Pros:**
  - Inductorless
- **Cons:**
  - Limited output current
  - Use of off-chip capacitors (large capacitors required 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



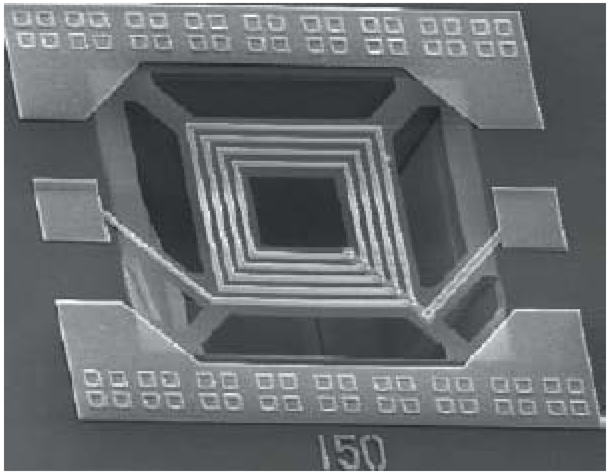
Conclusion: Good only for low-power applications.

Integrated Inductor Option

- **MEMS Approach:**

  Use of MEMS technology to fabricate on-chip inductors [1]

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!**

1 S.Iyengar, T.M. Liakopoulos and C.H. Ahn, "A DC/DC Boost Converter Toward Fully On-Chip Integration Using New Micromachined Planar Inductors," Proc. IEEE Power Electronics Specialists Conference, vol. 1, pp. 72-76, April 1999.

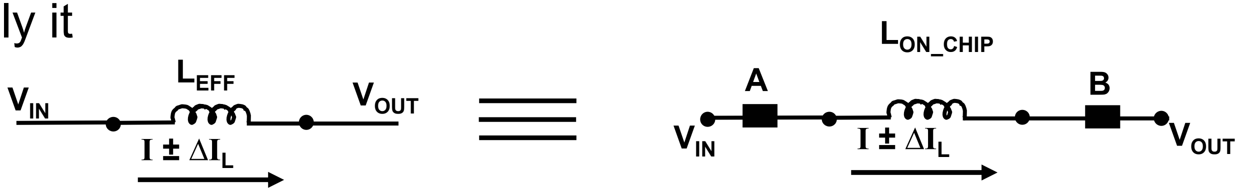
New Possible Approach

- **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

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

- 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.

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

- Implementation:
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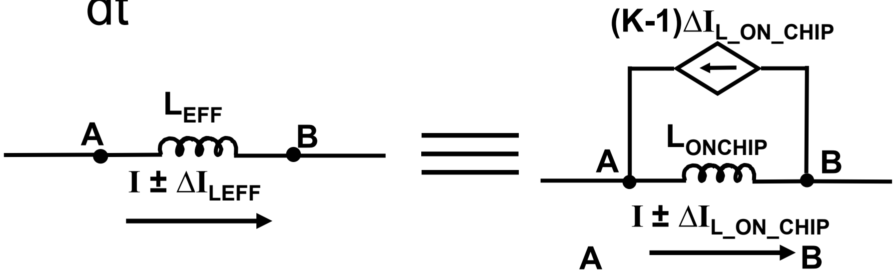
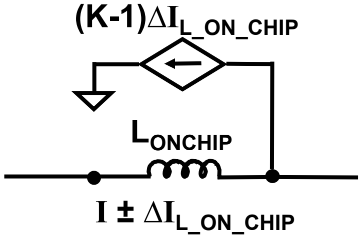


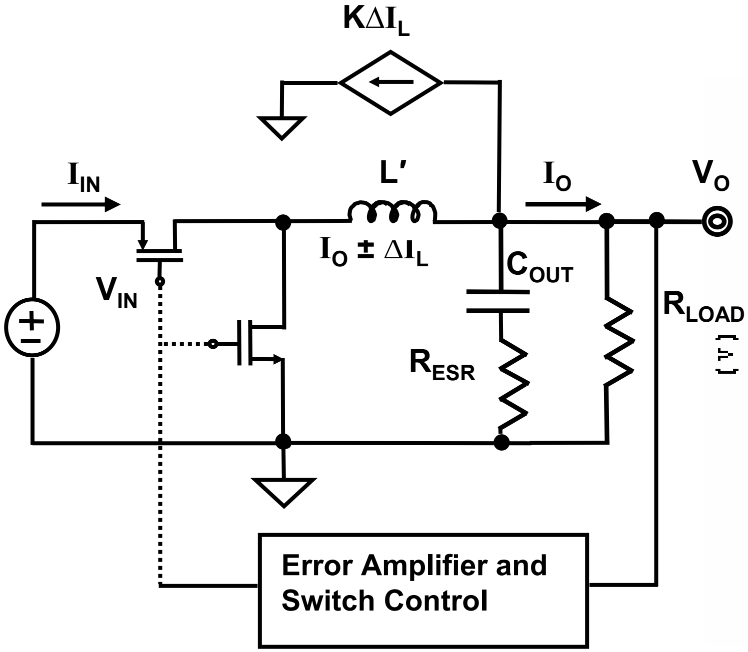
- Feasibility:

  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

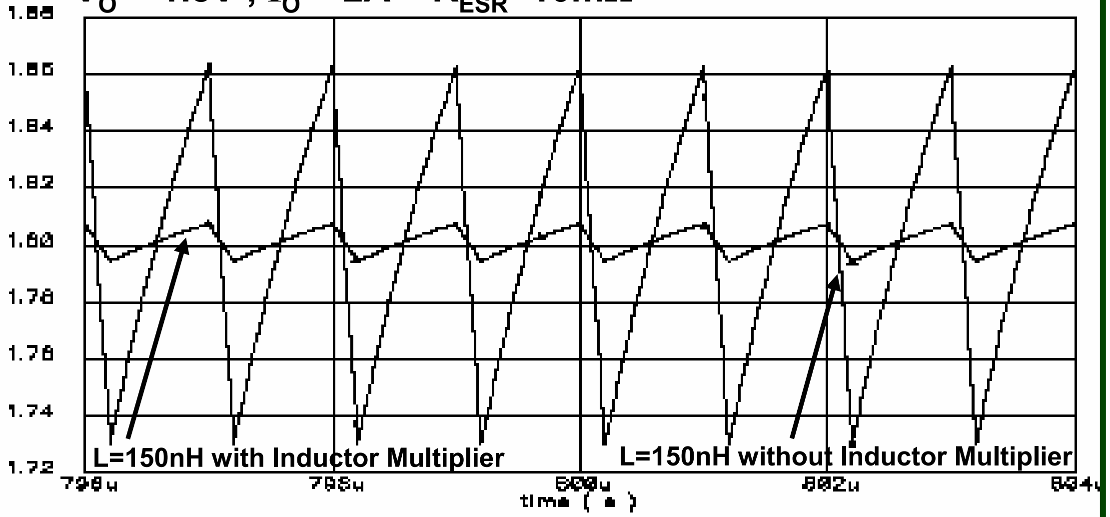
Buck converter with current mode inductor multiplier



Output Voltage with/without multiplier

V_{IN} (Li-ion) = 4.2-2.7V

V_O = 1.8V , I_O = 2A R_{ESR}=10mΩ



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

	Charge Pumps	External Inductor	Linear Regulators	MEMS Approach	Inductor Multiplier
SOC Feasibility *	Worst	Worst	Better	Good	Best
Output Power	Low	High	Low	Medium	Medium
Cost (PCB Estate)	High	Highest	Lowest	High	Low
Efficiency	Good	Best	Worst	Poor	Average

** 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 does 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.