Inductor Multipliers for DC-DC Converters

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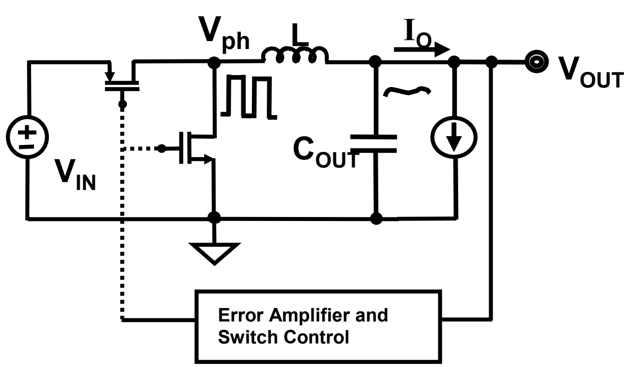
Introduction

- **Mobile, battery-powered applications require:**
  - » Low Voltage, High Efficiency, High Power, High Accuracy solutions.
  - » SOC → Integrated Power Supply circuits (dc-dc) → Integrated Power Inductors
- **State-of-the-art:**
  - » **External inductor** → Take-up PCB Real Estate → Add Cost
  - » **Integrated inductor** → Low-Power Applications → Low Efficiency
  - » **MEMS inductor** → Compatible with most fabrication processes → Low quality (Q) factor.
  - » **Charge Pumps** → No Inductors are needed → Very low power applications
  - » **Linear Regulators** → Poor efficiency → Low power applications
- **Goal:**
  - » **Integrate Power Inductors** onto the die/package and multiply the effects of a small integrated inductor using **Inductor Multipliers).**

WHY AN INDUCTOR ?



- Makes **efficient energy transfer** to load.
- Digital Signal at V_{ph}; LC **filters** it to V_{OUT}
- L determines output current ripple **(**ΔI_L), voltage ripple **(**ΔV_{OUT}**)**, and **bandwidth**.

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

Proposed Approach - Inductor Multiplier

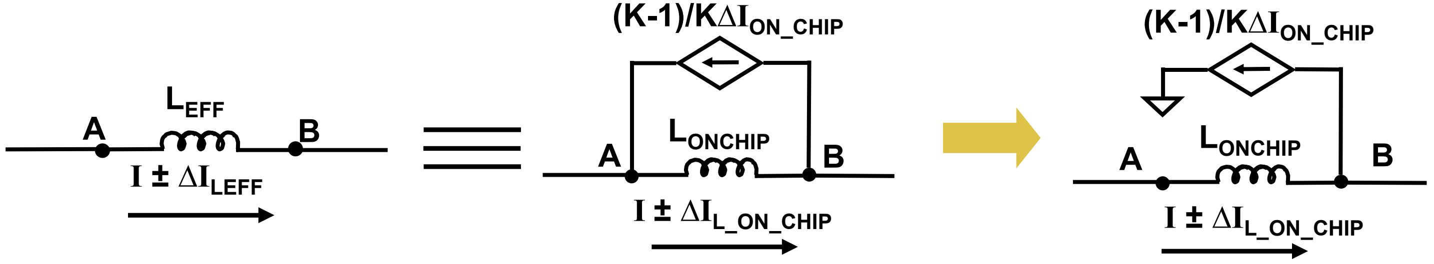
- **Operation:**

» The voltage across the inductor is constant therefore to enhance the value of inductor, current is increased.

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

- **Implementation:**

» Use a current-controlled-current-source to sense the ripple current through the inductor, and subtract a portion of it from the node .



- $\Delta I_{L\_ON\_CHIP}$ = K X ΔI_{LEFF}
- L_{EFF} = K X L_{ON_CHIP}

❑ **Issue:**

» The potential at node A is greater than B, hence the flow of current is not realizable.

❑ **Solution:**

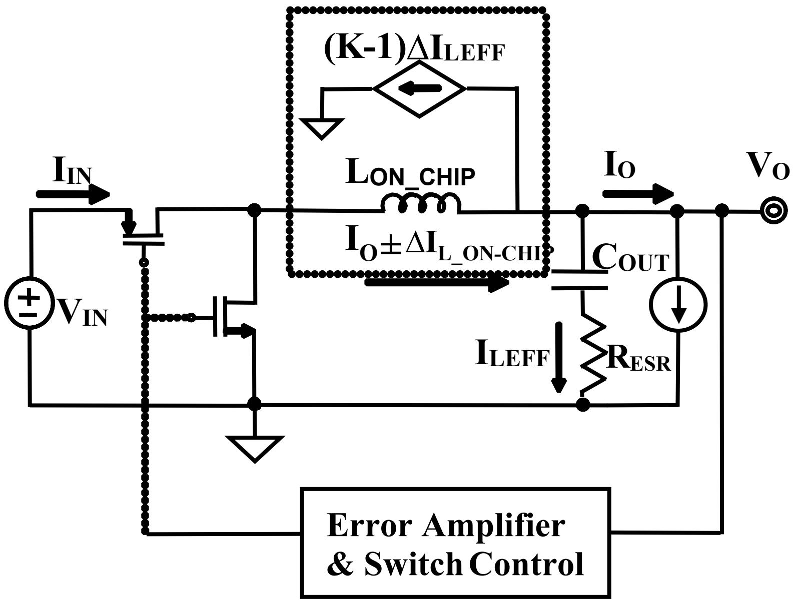
» Since A is a low-impedence node, take the current to ground.

❑ **Trade off:**

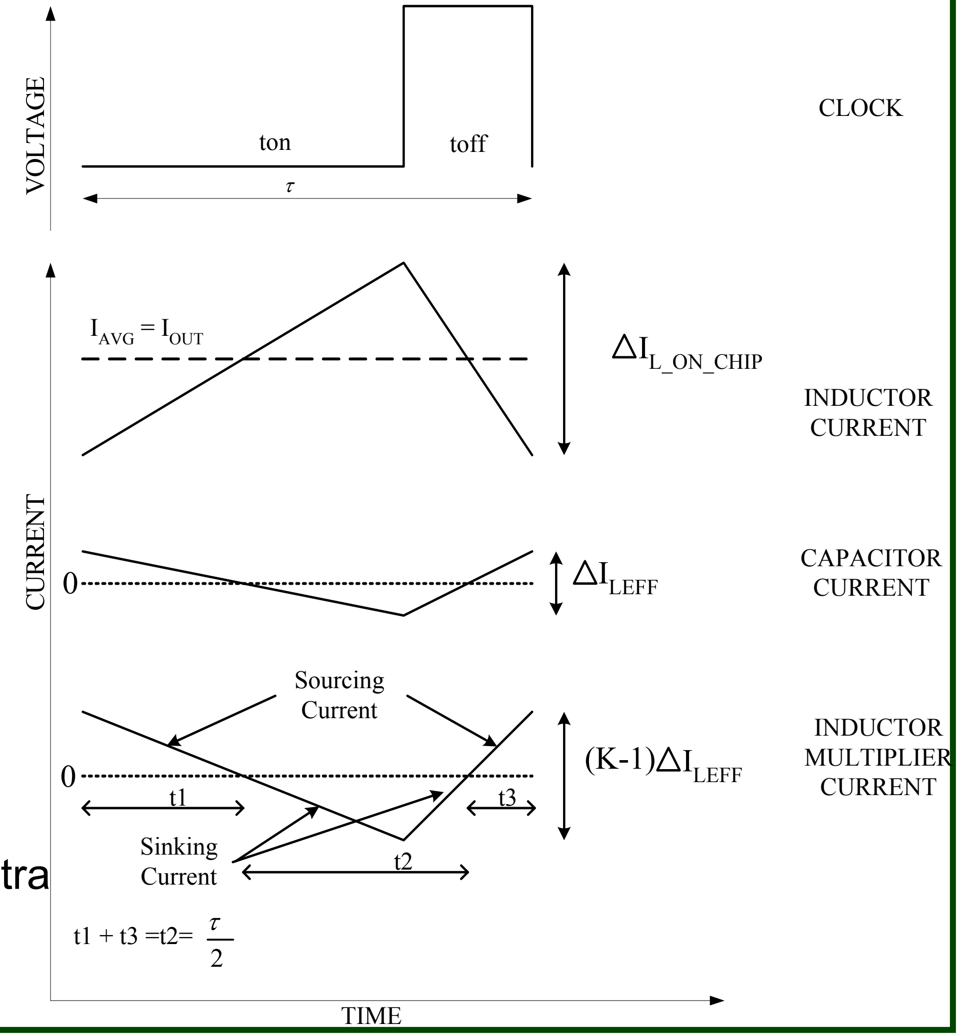
» Increased losses and hence reduced efficiency.

Proposed Approach - Inductor Multiplier

Buck-converter with the inductor multiplier.



Current waveforms of the inductor multiplier in a buck-converter.



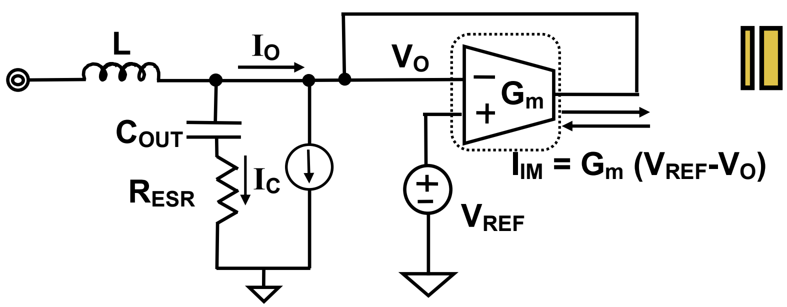
- For times t1 &t3, $I_L < I_{OUT}$; Inductor multiplier sources the required current.
- For t2, $I_L > I_{OUT}$; Inductor multiplier sinks the extra current.

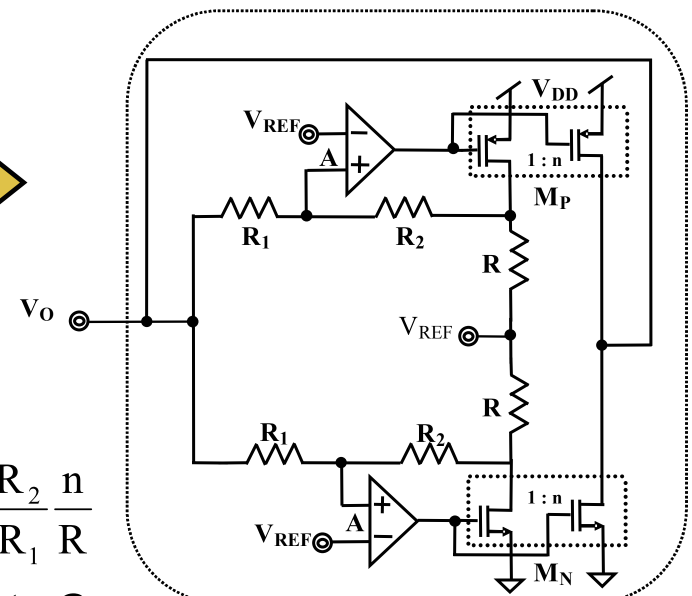
Proposed Approach – Implementation

- **Ideal implementation:** Sense the current accurately and amplify it.
  Cons: Accurate current sensing techniques are either lossy or complex.
- **Proposed implementation:**
  » In a buck converter:

$$V_{OUT} = V_C + V_{ESR} + V_{ESL} \approx V_{ESR} = I_C R_{ESR}$$

I_C: capacitor ripple current ≡ ΔI_L
For electrolytic capacitors, the voltage ripple is **ESR dominant**.





$$G_m = \frac{R_2}{R_1}\frac{n}{R}$$

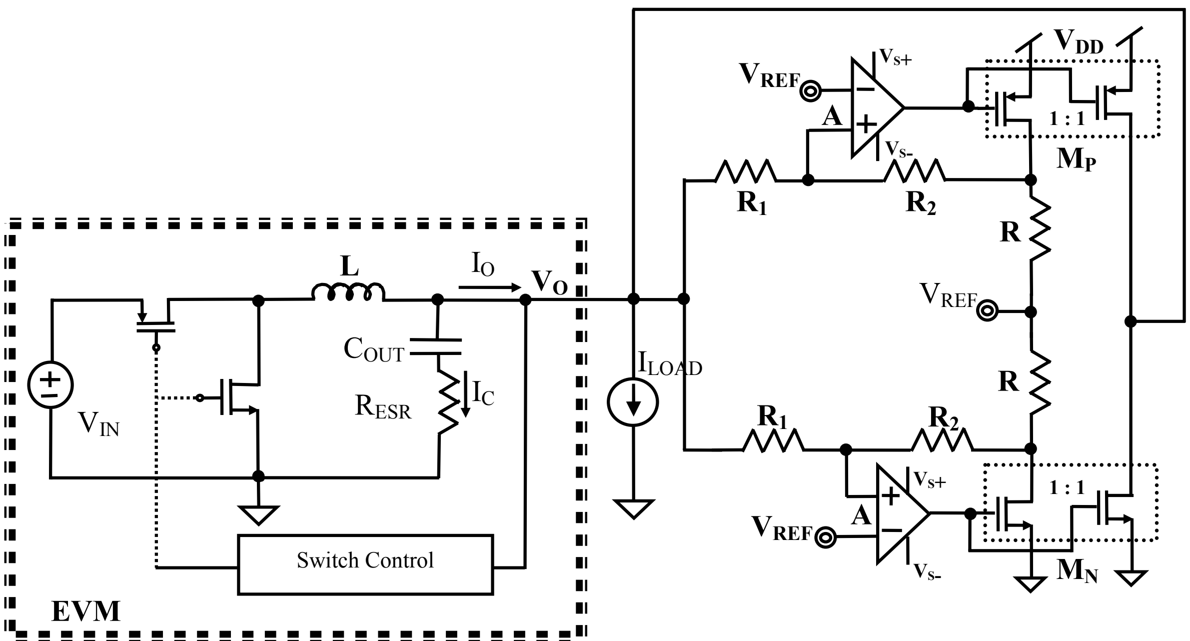
If $V_O > V_{REF}$, G_m sinks current
If $V_O < V_{REF}$, G_m sources current

$$G_m = \frac{K-1}{R_{ESR}}$$ (K: multiplication factor)

- Accurate G_m
- Low I_Q
- Bandwidth Limited

Proposed Approach – Implementation

• **Prototype Implementation of Inductor Multiplier**



$$G_m = \frac{R_2}{R_1}\frac{1}{R} = 80$$

$$f_{-3dB} \ @ \ A_{CL} = \frac{R_2}{R_1} = 10^* f_{SW}$$

R= 1Ω, to obtain large G_m since mirror ratio n=1

For the integrated version n~1000, R~20Ω and GBW~10MHz

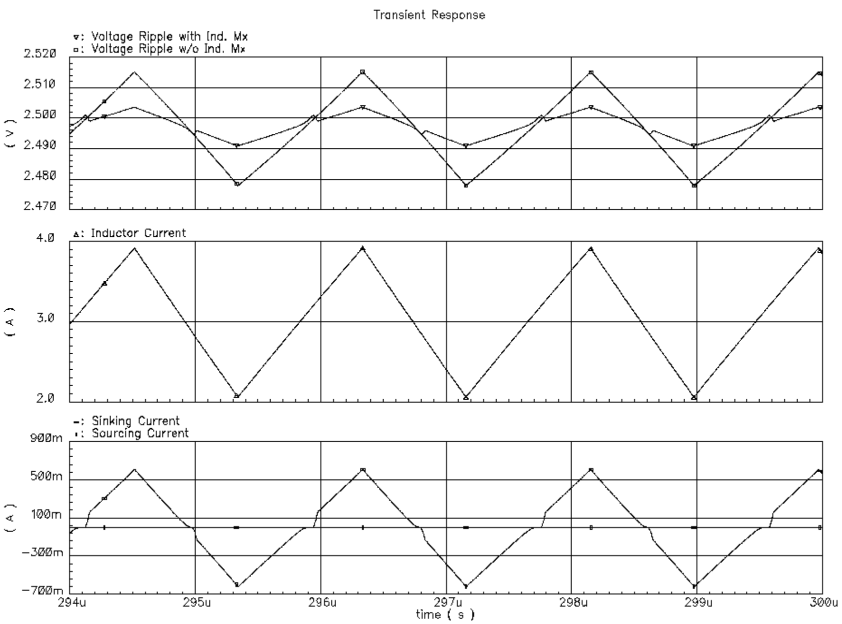
EVM-TPS54610
V_{IN}: 5V
V_O: 2.5V
I_{LOAD}: 0-6A
f_{sw}: 550 kHz
L=1.2uH
R_{ESR} in the EVM is ~15-20 mohms.

Inductor-Multiplier (M=2.7)
V_{DD}: 5.0V
V_{REF}: 2.5V
R: 1Ω
R_1:100Ω, R_2: 8kΩ

High-Speed Amplifier –A (THS 4271)
Gain Bandwidth ~ 500MHz
$V_S \pm = \pm 6.0V$
Matched Transistors
M_N: NDS9945 (Imax =3A)
M_P: NDS9948 (Imax=3A)

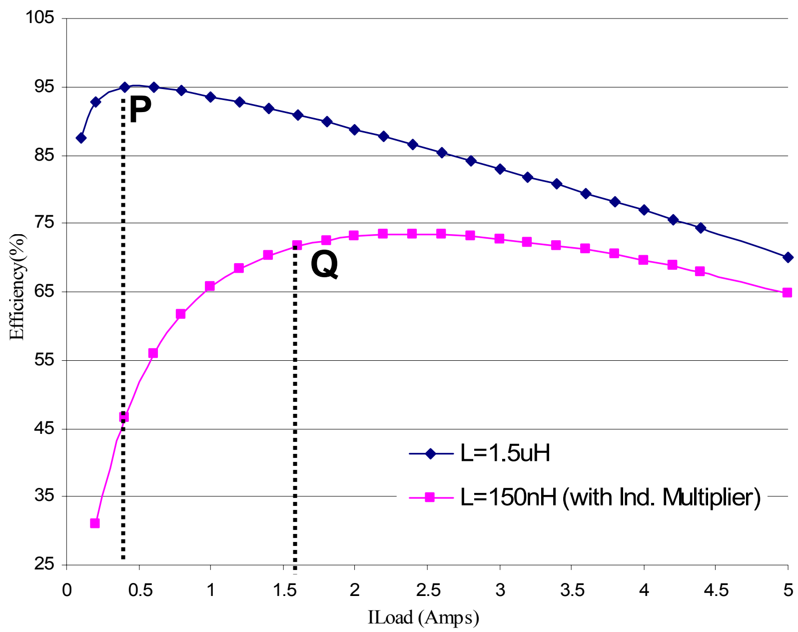
Simulation Results

Simulation Results of the Prototype



V_{IN} = 5V, V_O = 2.5V , I_O = 2.5A R_{ESR}=15mΩ
L=1.2uH multiplied to 3.3uH

Efficiency Vs Load Current - Comparison



- Onset of negative I_L at P and Q.
- Peak Efficiency (η) = 74%, @ I_{LOAD} = 2.5A and Multiplication factor=10. (η = 70% for Linear Regulators).

Conclusions & Future Work

	Charge Pumps	External Inductor	Linear Regulators	MEMS Approach	Inductor Multiplier
SOC Feasibility	Worst	Worst	Best	Good	Best
Output Power	Low	High	Low	Moderate	Moderate
Cost (Process Tech.)	High	Highest	Low	High	Low
Efficiency	Good	Best	Worst	Poor	Moderate
Complexity	Good	Good	Best	Poor	Poor

- **Conclusion**
  - Inductor multiplier ➔ SOC/SOP Solution ➔ medium power portable applications.
  - Provides **better efficiency than the linear regulator.**

Future Work:

- Investigation of techniques for the **integration of the inductor.**
- Evaluate the performance of the prototype and move towards **integrated solution**.