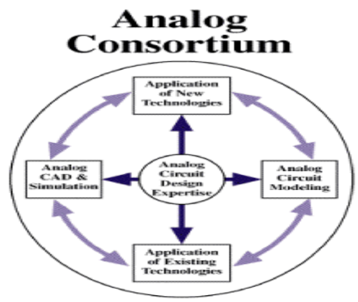
Prototype Implementation of a New, Accurate, and Lossless Current-Sensing Technique Suitable for Integrated Solutions



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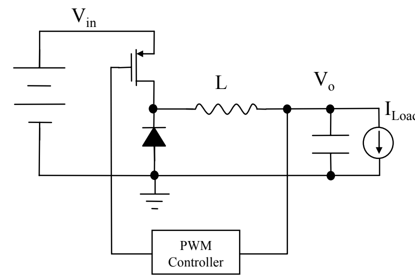
March 21, 2003

Abstract

Portable, single-cell battery devices use switching regulators to convert the battery voltage to required subsystem's voltage levels, efficiently. For various reasons, switching regulators demand information about the inductor current. Available current-sensing techniques are not both lossless and accurate at the same time. To address this issue, a current-sensing scheme is proposed that is lossless, accurate, and suitable for integrated solutions. A prototype of the system is under progress, and preliminary results verify the design concept.

Review of The Problem

- Why current-sensing?
  - Over-current protection
  - Current-mode control
  - Mode hopping (A technique to obtain high efficiency at all loads)
  - Current sharing

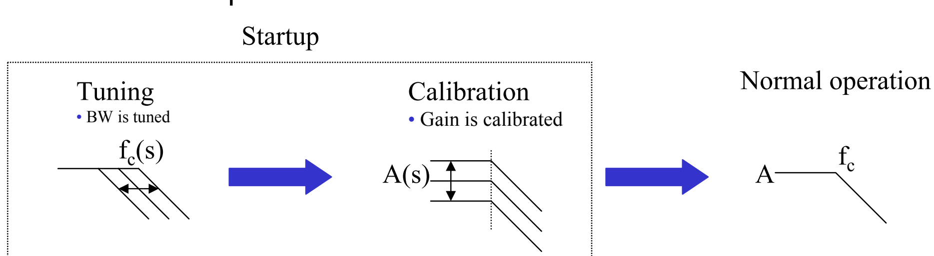


- Why not the conventional way of current sensing (resistor in the path of the current to be sensed)?
  - High power dissipation in the sense resistor
  - Degradation of efficiency (Not lossless)

- Why not other lossless techniques?
  - Not accurate
  - Dependent on off-chip elements
  - Not suitable for integrated solutions

Proposed System at a Glance

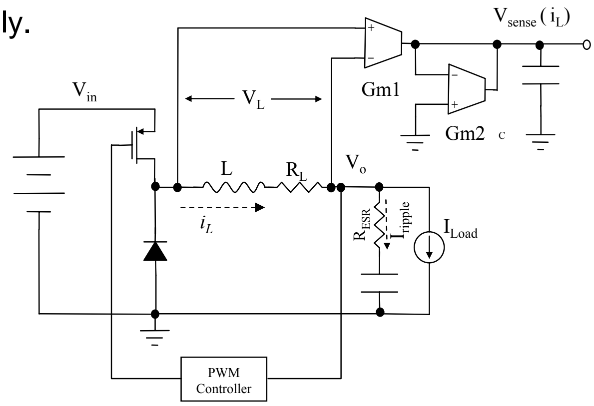
- Proposed system uses a first-order low pass Gm-C filter to imitate the inductor behavior.
- The Gm-C filter input is the voltage across the inductor.
- If the cutoff frequency of the Gm-C low-pass filter is equal to the cutoff frequency of the inductor (caused by L and R_L), the Gm-C filter output is proportional to the inductor current.
- The proposed system operation consists of three stages:
  1- Tuning (during startup)
  2- Calibration (during startup)
  3- Normal operation



Normal Operation

IF the Gm-C filter matches the inductor characteristic, the output sense voltage estimates the inductor current accurately.

$$\begin{cases} I_L = \dfrac{1}{(R_L + sL)} V_L \\ V_{sense} = \dfrac{Gm1}{Gm2}\left(\dfrac{1}{1+s(C/Gm2)}\right) V_L \end{cases}$$

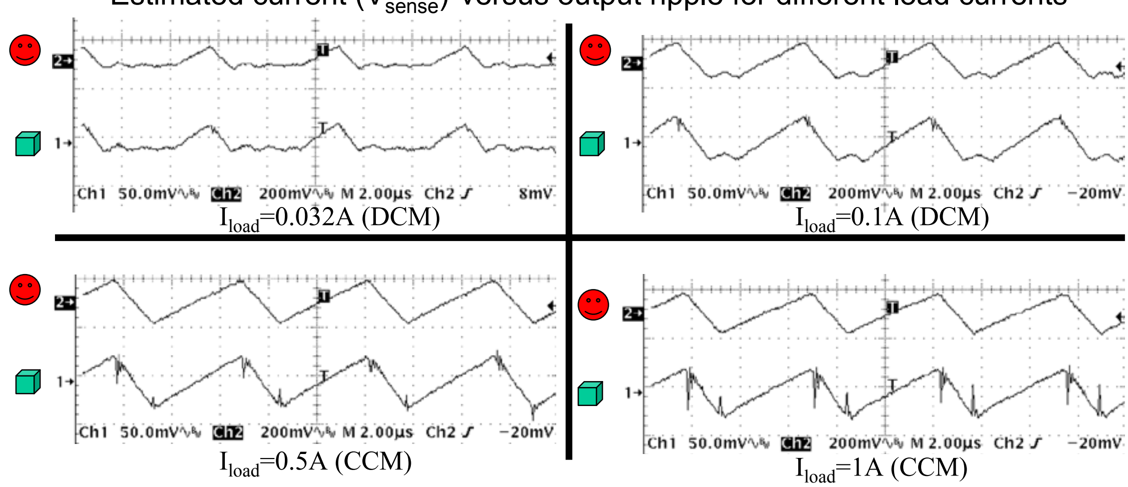


If $(L/R_L)=(C/Gm2)$ ➡

$$V_{sense} = \left(\frac{Gm1}{Gm2} R_L\right) \times 1\Omega \times I_L$$

Normal Operation Experimental Results

Estimated current (V_{sense}) versus output ripple for different load currents



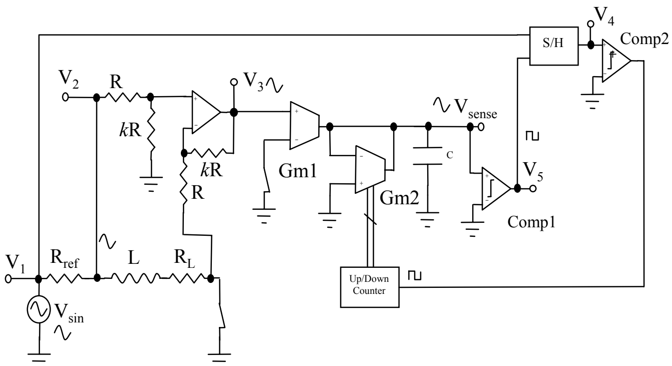
1: Output voltage ripple α ΔI

2: Proposed system output (estimated current)

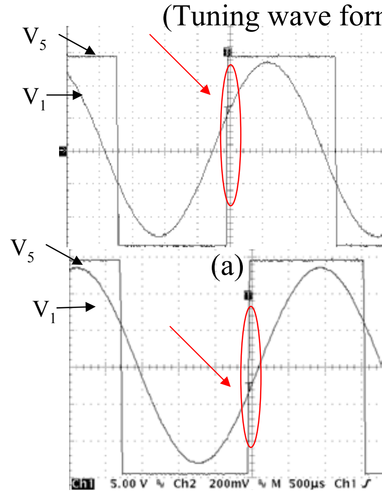
- Since the capacitor ESR is high (in the prototyped DC-DC converter), the output voltage ripple is proportional to the inductor current ($\Delta V_{out}=R_{ESR}I_L$).

Tuning

- Loop forces equal phases for V_{sense} and V_1.
- Tuning range is determined by Gm2.



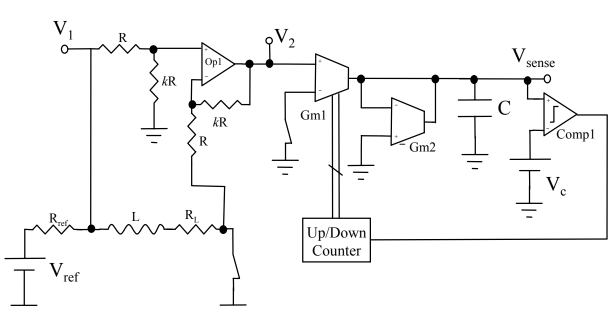
(Tuning wave forms)



(b)

The phase difference between V_1 and V_5 varies by changing the Gm2 bias current. Phase difference for (a). $Gm2_{min}$, and (b). $Gm2_{max}$. V_1 is a sinusoidal signal with magnitude of 2 V_{pp}, and frequency of 500Hz.

Calibration



Calibration process adjusts the low-frequency gain.

Calibration:
$V_{sense} = V_c \rightarrow I_{ref}.R_L.k.Gm1/Gm2 = V_c$

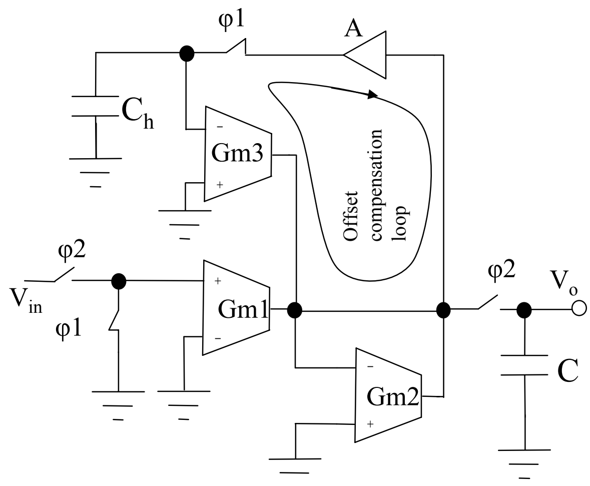
Normal operation:
$V_{sense} = I_L R_L Gm1/Gm2$
$= I_L V_c/(kI_{ref})$

IF $V_c/(kI_{ref})=1 \rightarrow V_{sense}=1\Omega\times I_L$

Problem:
The Gm1 offset depends on the bias current → Simple offset cancellation does not work → More advanced, dynamic offset cancellation is required.

Closed-Loop Offset Cancellation Technique[1]

Offset is cancelled by the additional current provided by Gm3.

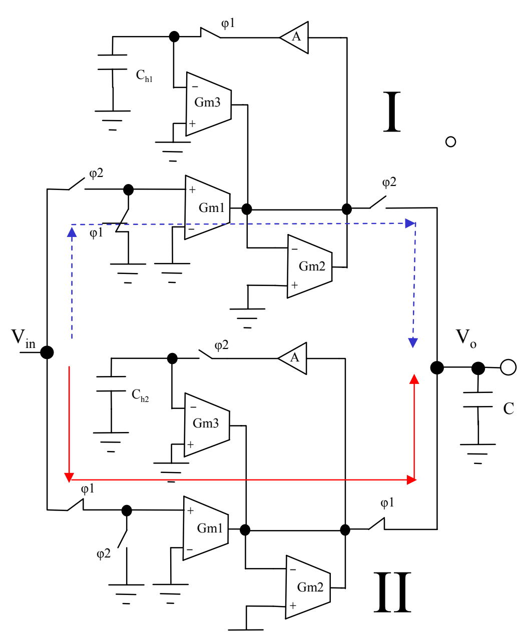


- During φ1
  - Compensation loop is closed.
  - Input voltage is zero.
  - Output voltage is set to zero by the Gm3 output current.
- During φ2
  - Compensation loop is opened.
  - Circuit performs its normal operation.
- Problem:
  Operation is not continuous
- Solution:
  Ping-pong configuration can be used.

[1] C. Enz and G. Temes, "Circuit techniques for reducing the effects of op-amp imperfections: autozeroing, correlated double sampling, and chopper stabilization," Proceedings of IEEE, Vol.84, 1996, pp. 1584-1614.

Ping-Pong[2] Operation

Using two of the previous circuits in parallel, the operation becomes continuous. While one of the circuits works in the normal operation, the other one adjusts and cancels its offset.



- Two matched gm-C filter sets are used.
- Each gm-C set uses a closed loop offset cancellation.
- During φ1:
  - Sub-circuit (I) cancels its offset.
  - Sub-circuit (II) filters the input signal.
- During φ2:
  - Sub-circuit (I) filters the input signal.
  - Sub-circuit (II) cancels its offset.

[2] Y. Chong-Gun Yu and R. Geiger, "An automatic offset compensation scheme with ping-pong control for CMOS operational amplifiers," IEEE Journal of Solid-State Circuits, Vol. 29, 1994, pp. 601-610.

Conclusions and Future Work

- Conclusions:
  - Concept works
  - Problem with calibration

- Future work:
  - Completion of the prototype system
  - Integration of the circuit
  - Addition to a low-voltage boost converter for control, and mode hopping