An Integrated, Lossless, and Accurate Current-Sensing System for High-Performance DC-DC Converters

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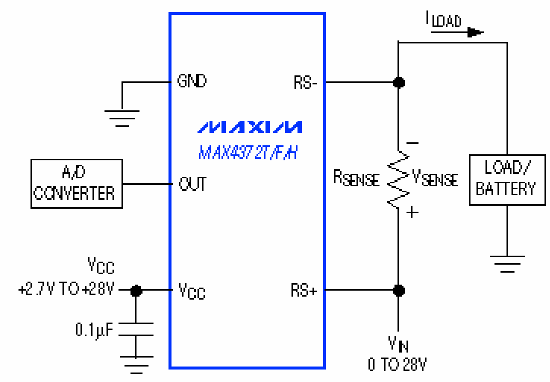
Abstract

Abstract:

Current-sensing circuits are essential for protection and control of the switching regulators. Inserting a resistor in the path of the current to be sensed reduces the converter efficiency by 3-8%. Therefore, lossless current-sensing circuit should be used to meet the efficiency specification of the high-performance converters (more than 90% efficiency at all loads). However, without the knowledge of off-chip elements, lossless current-sensing circuits are not accurate, which would introduce errors in protection, control and efficiency enhancement circuits that use current information. A current-sensing technique that is both lossless and accurate was proposed, which measures the inductor during the start-up. The error sources as well as the methodology for integrated implementation of the technique are discussed in this poster.

Why Current Sensing?

- Over-current protection
  (especially for lasers and audio AC-DC converters)
- Additional state for converter control- simplifies the compensation
  (i.e., current-mode and boundary control)
- Mode hopping
  (A technique to obtain high efficiency at all loads)
- Current sharing
  (parallel/multi-phase converters)
- Single-inductor multiple-output converters (SIMO)
  (D. Ma, 2003)

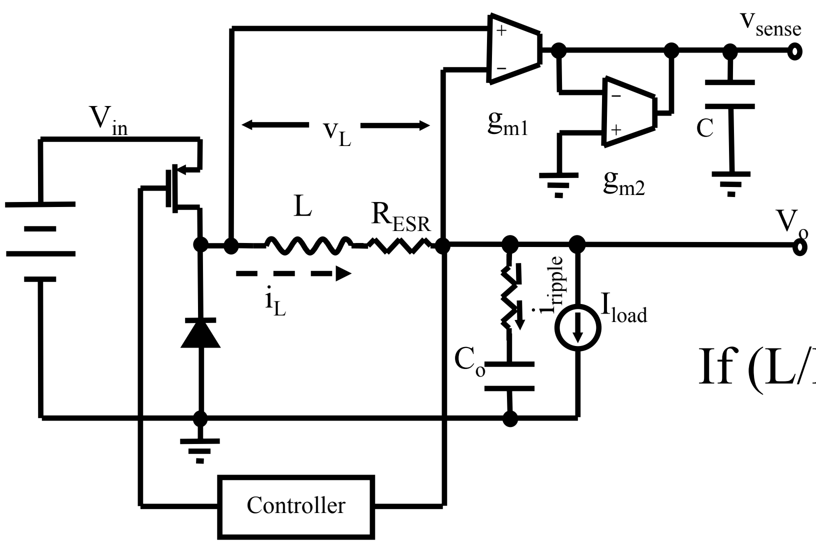


Available Techniques

Technique	Advantages	Disadvantage
A. R_{SENSE}	Accuracy	High power dissipation
B. R_{DS}	Lossless	Low accuracy
C. L_{Filter}	Lossless	Known L and ESR High number of discrete elements
D. Observer	Lossless	Known L
E. $I_{Average}$	Lossless	Known inductor ESR Average inductor current only
F. Transformer	Lossless	Cost Size Not integrable No I_{DC} information Not practical
G. Sense-FET	Lossless Integrable Practical	Special MOSFETs (not suitable for off-chip switches) High Switching noise, specially at low duty cycle Accuracy of about ±20%
H. Hall Effect Sensor	Lossless	Very low sensitivity in standard CMOS (no ferromagnetic material, low bandwidth, no commercial or academic report on DC-DC converters)

e techniques are not lossless, and lossless tech are not accurate.

Filter Technique Enhancement



$$\begin{cases} i_L = \dfrac{1}{(R_{ESR} + sL)} v_L \\ v_{sense} = \dfrac{g_{m1}}{g_{m2}} \left(\dfrac{1}{1 + s(C/g_{m2})} \right) v_L \end{cases}$$

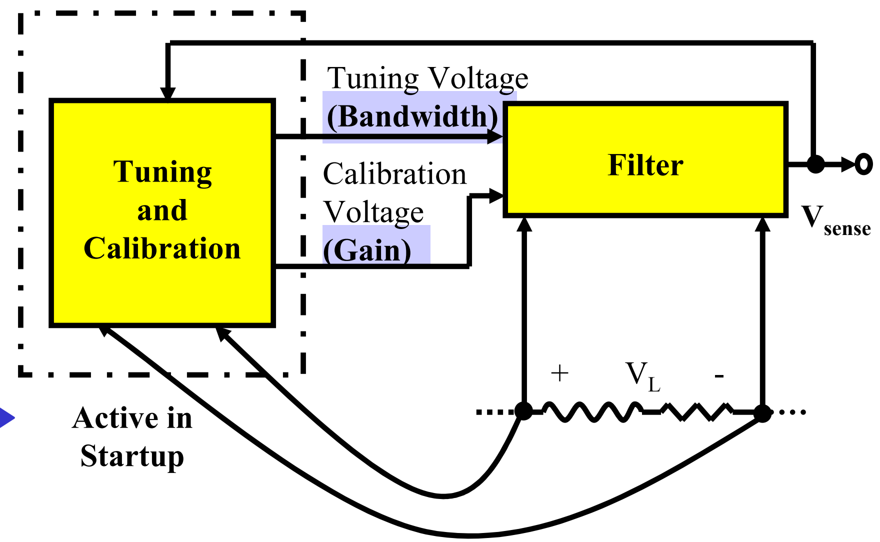
If $(L/R_{ESR}) = (C/g_{m2})$ → $v_{sense} = \left(\dfrac{g_{m1}}{g_{m2}} R_{ESR} \right) \times I_L$

Problem:

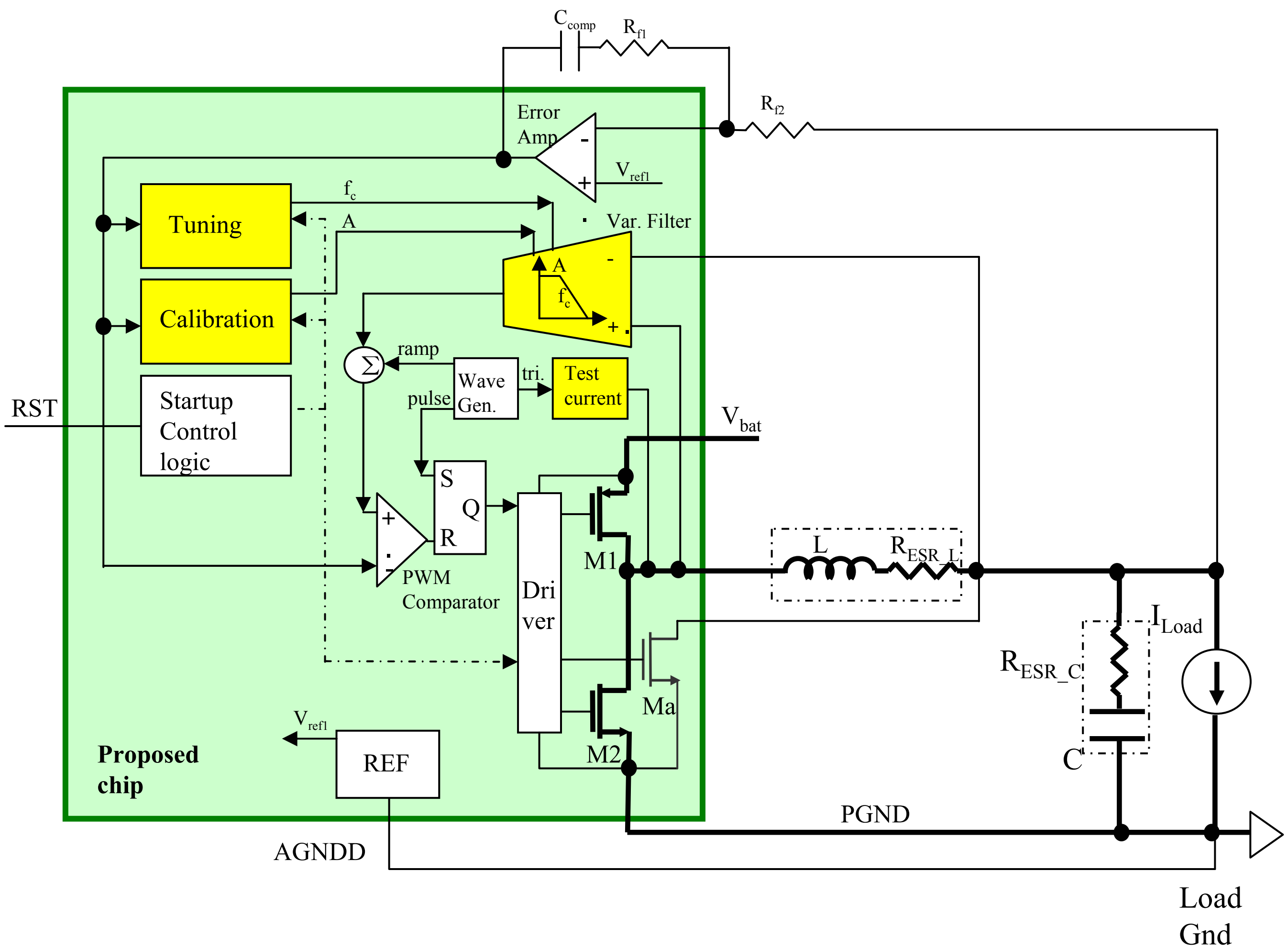
L and R_L are not known to IC designer

Enhancement:

Measure L and R_L at the system Startup.



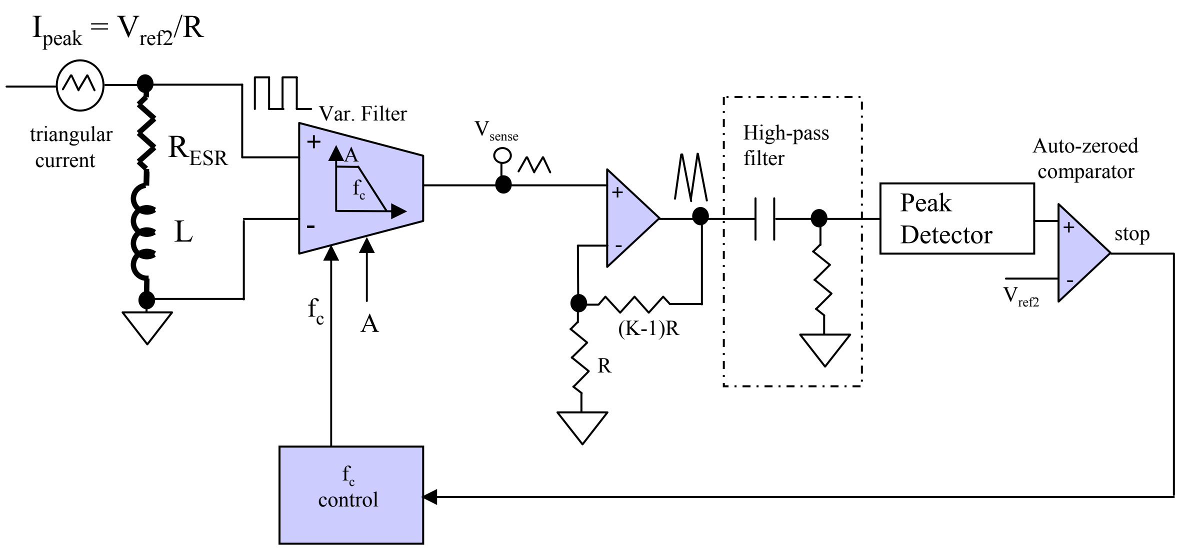
Proposed System



- Buck converter
- V_{in}=2.7V-5V
- V_{out}=1.8V
- f_s=1MHz
- I_{load}>1A
- Current-mode PWM Controller
- Current-sensing accuracy <7.5% at full load current over temperature and load current range.
- Inductor range
  inductance: 2uH-8uH
  ESR: 25mΩ-100mΩ
- Temperature range:
  T=-40°C-85°C

Tuning/Calibration

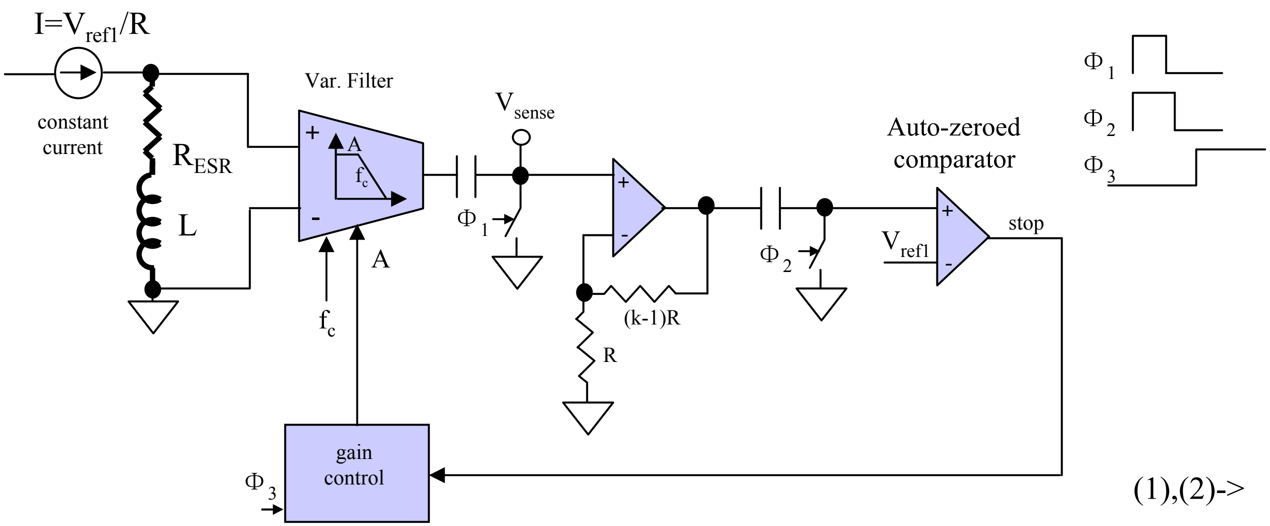
Tuning
(AC gain adjustment)



$$K g_{m1} \frac{L}{C} I_{peak} = V_{ref}$$

$$g_{m1} = \frac{V_{ref}}{K I_p} \frac{C}{L} \qquad (1)$$

Calibration
(DC gain adjustment)



$$K \frac{g_{m1}}{g_{m2}} R_{ESR} I_{ref} = V_{ref}$$

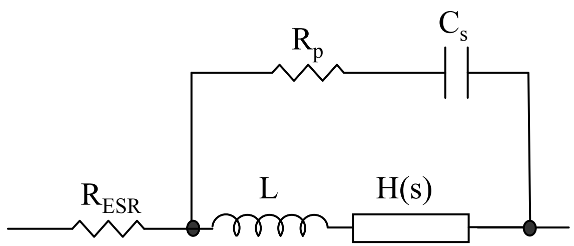
$$\frac{g_{m1}}{g_{m2}} R_{ESR} = \frac{V_{ref}}{K I_{ref}} \qquad (2)$$

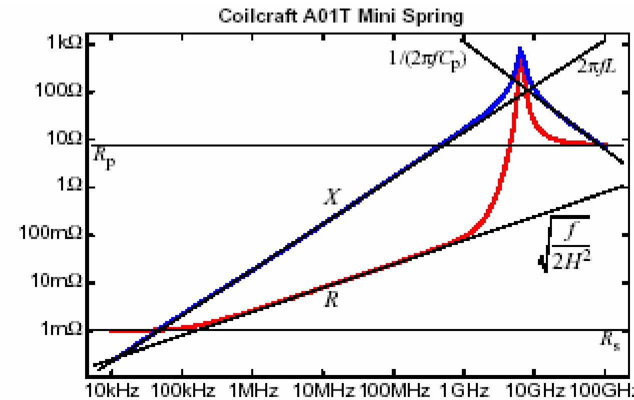
(1),(2)->

$$\frac{C}{g_{m2}} = \frac{L}{R_{ESR}}$$

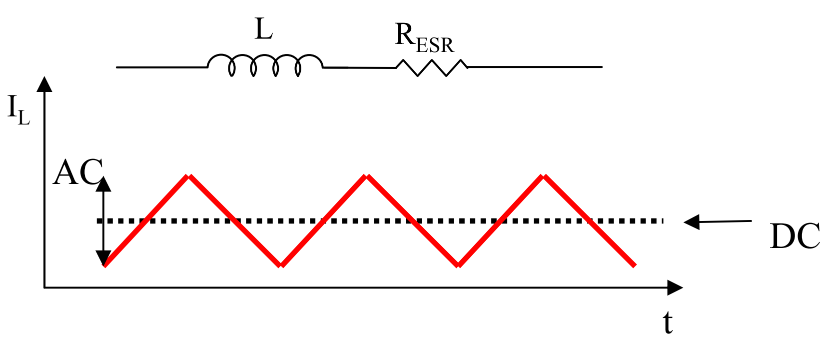
Power Inductor Model

Inductor Model

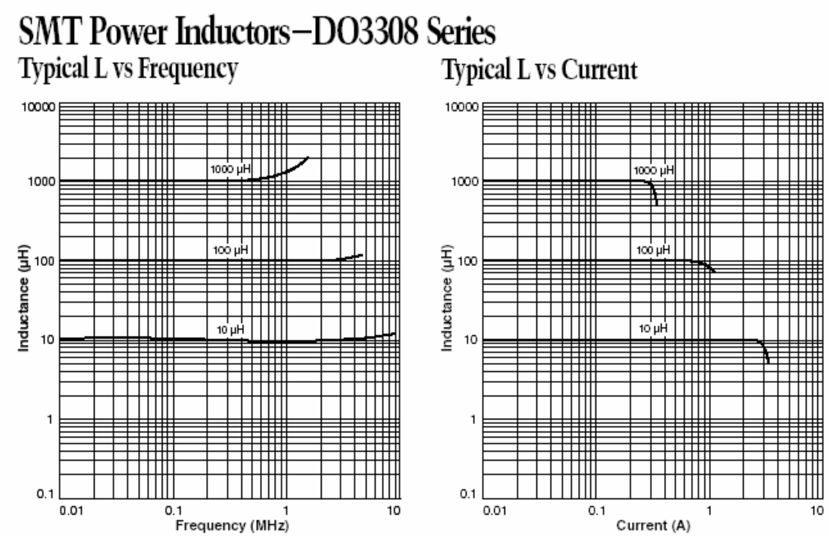




Simplified Inductor Model for Power Inductors



R_{ESR} determines the current DC value.
L determines the current AC value.



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Error Sources

Error source	Nature of error	% Error	Systematic /Random	Predictability[2]	Compensation
L vs. Temperature T=-40°C -85°C	200-800ppm/°C ±1.25%-±5%	AC: ±1.25%-±5%	Systematic	Medium	Maybe
$R_{ESR\ vs.\ Temperature}$ T=-40 to 85	3900ppm/°C±2%	DC: ±25%	Systematic	High	Yes
L versus I_L	Core saturation	AC: 0-20% DC: 0-4%	Systematic	Low	No, Proper selection of inductor
$R_{ESR\ versus\ IL}$[1]	-	-	-	-	-
$R_{ESR\ vs.\ frequency}$	Parasitic capacitor Skin effect	AC: 0 DC: <1%	Systematic	Medium	No
L versus frequency	1-3% change per decade	AC: <1% DC:0	Systematic	Low	No, Proper tuning

(1) This effect is considered in R_{ESR} versus temperature.

(2) Predictability determines how well an IC-designer can predict and compensate the error source at the design time.

Conclusions

- Proposed system uses a first-order low-pass filter to imitate the inductor behavior.
- The filter input is the voltage across the inductor.
- If the cutoff frequency of low-pass filter is equal to the cutoff frequency of the inductor (caused by L and R_L), the 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
- The accuracy of the system is limited by the compensation of inductance changes with environmental parameters (i.e., temperature).