Modelling and Validation of High-Current Surface-Mount Current-Sense Resistor

Josip Bačmaga[1], Raul Blečić[1], Renaud Gillon[2], Adrijan Barić[1]

[1]University of Zagreb, Croatia
Faculty of Electrical Engineering and Computing

[2]ON Semiconductor
Oudenaarde, Belgium

22nd IEEE Workshop on Signal and Power Integrity (SPI) 2018
Measurement and Characterization – Session 8

Brest, France; 25 May 2018

This work was supported by the Croatian Science Foundation (HRZZ) within the project “Advanced design methodology for switching dc-dc converters”.

hrzz

Hrvatska zaklada za znanost

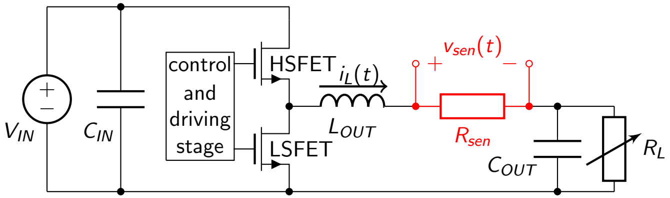
Outline

Outline

1. Introduction
2. Measurement Procedure
3. Lumped-Element Model of the Current-Sense Resistor
4. Validation of the Model
5. Conclusion

Introduction

- High-frequency switching voltage regulators
  - decrease of physical dimensions
  - increase of AC power losses
  - ⇒ precise current sensing to evaluate losses (inductor performance)
- Extracting the inductor current waveform ($i_L(t) = v_{sen}(t)/R_{sen}$):



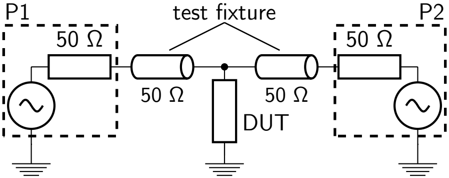
- High-power R_{sen} ⇒ large dimensions ⇒ parasitics ⇒ **model**

Motivation

Main goal: make a very precise model of the current-sensing resistor used to evaluate losses in the inductor of the DC-DC converter and exact current up to several harmonics of the switching frequency where the skin effect losses are more pronounced.

Introduction

- Model extracted from S-parameter measurements
- Two-port shunt measurement method:



✓ low-impedance DUT not in the series to the impedance of the test fixture

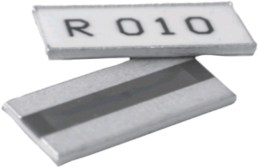
✗ one port tied to ground (pad-ground capacitance shorted out)

Outline

Measurement Procedure

Device under test:

- typical test case from family of high-power current-sense resistors,
- Ohmite FCSL150R050FER,
- nominal resistance: 50 mΩ,
- rated power: 10 W,
- $w \times l \times t = 15 \times 7.5 \times 1.1$ [mm].



Designed measurement structures:

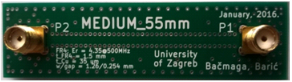
- calibration structures for de-embedding test-fixture parasitics,
- two-port shunt characterization setup.

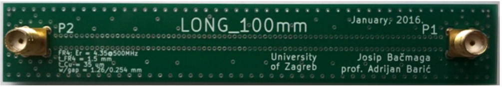
Conductor-backed coplanar waveguide, CBCPW ($Z_0 = 50\ \Omega$)**:**

- **copper** strip width: 1.26 mm, gap: 0.254 mm, thickness: 0.035 mm,
- **FR4 substrate** thickness: 1.5 mm.

Calibration Structures

- "CBCPW through",
- 30-mm, 55-mm and 100-mm



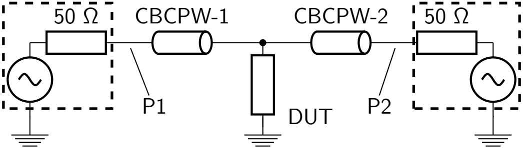


Test fixture modelling:

1) S-parameters measured (after VNA calibration)
2) model of test fixture in ADS,
3) parameters of connectors, interconnects and substrate optimized in ADS,
4) $\epsilon_r = 5.1$ (difference of phase shift of S_{21} from two cal. structures),
5) model of test fixture $\rightarrow$ de-embedding component in ADS.

Characterization Setup

- Two-port shunt structure:



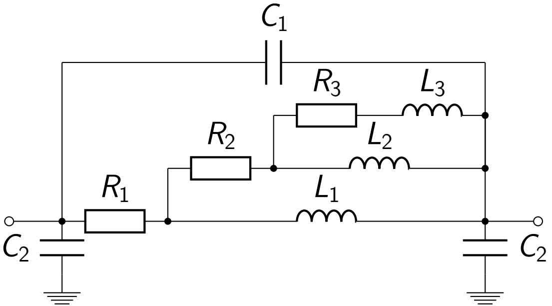
Measurement procedure:

1) S-parameter of DUT measured up to P1 and P2,
2) test fixture parasitics de-embedded from measured S-parameters,
3) Z-parameters calculated from measured S-parameters,
4) characterization setup represented by T-model (Z_3 to gnd),
5) model of DUT extracted: $Z_{DUT} = Z_3 = (z_{12} + z_{21})/2$.

Outline

Lumped-Element Model

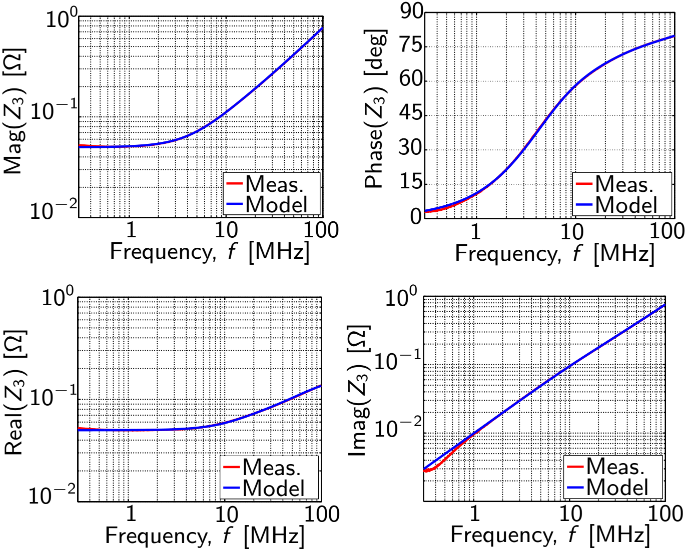
- Optimized in ADS to fit measured S-parameters



- R_1 – DC resistance (not optimized),
- L_1, R_2-L_2, R_3-L_3 – skin effect,
- C_1 – pad-pad cap.,
- C_2 – pad-gnd cap.

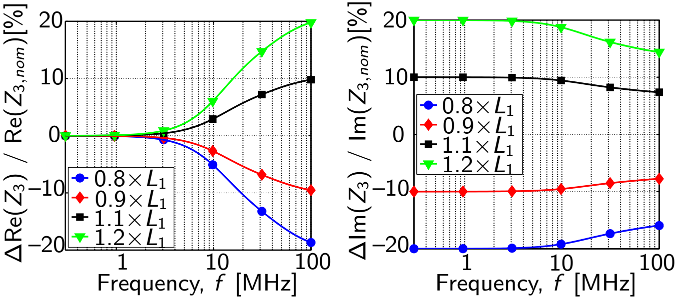
R_1, mΩ	L_1, nH	R_2, mΩ	L_2, nH	R_3, mΩ	L_3, nH	C_1, pF	C_2, pF
50.30	1.57	867.75	5.51	6472.70	12.92	15.51	2.76

Model vs. Measurements



Variation of parameter L_1

- Impact of $\pm 10\%$ and $\pm 20\%$ variation on impedance of the model

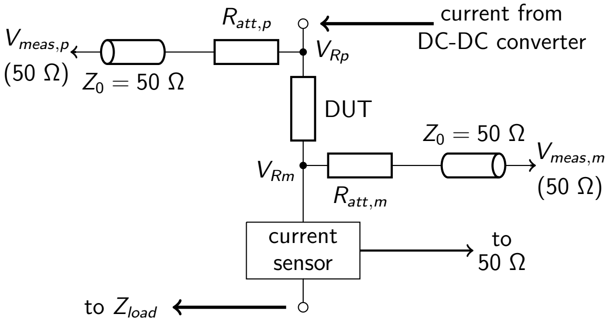


- L_1 → skin effect → impact on real part at high freqs,
- impact of R_2-L_2 and R_3-L_3 networks is similar.

Outline

Validation Setup

- Part of a DC-DC converter:

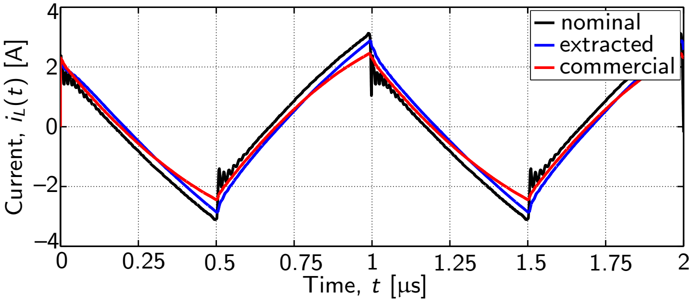


- V_{Rp} and V_{Rm} – voltage across DUT (50-Ω probes),
- $R_{att,p}$ and $R_{att,m}$ – prevent current flowing into probes,
- commercial current sensor – large bandwidth,
- Z_{load} – short at frequencies of interest.

Time Domain

Extracting the ripple current waveform (1 MHz):

- $V_{meas,p}$ and $V_{meas,m}$ $\rightarrow$ SPICE (piecewise linear) $\rightarrow$ $i_L(t)$
  - nominal (pure 50-mΩ model)
  - extracted model
- large-bandwidth commercial current sensor

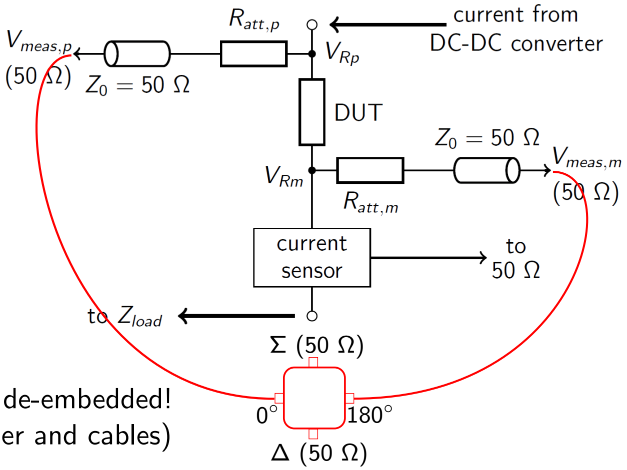


- recorded using Agilent MSO7034B oscilloscope (50-Ω channel imp.)

Frequency Domain

Extracting the current spectrum (using spectrum analyzer):

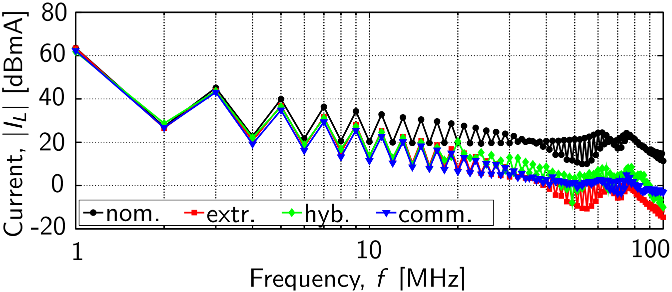
- nominal (50-mΩ) and extracted model, commercial sensor,
- extracted model, measured using R&K PH010 hybrid coupler.



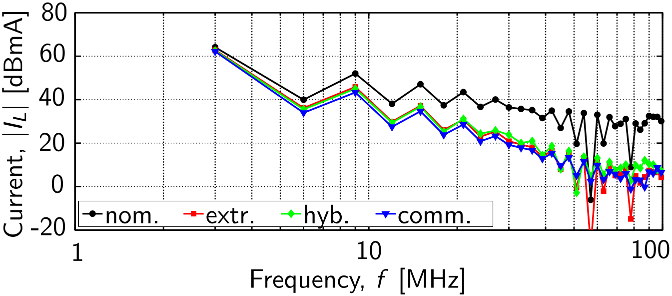
test fixture de-embedded!
(hyb. coupler and cables)

Frequency Domain – Test Cases (I)

1) $f_{sw} = 1$ MHz, $I_{L,p-p} = 5$ A



2) $f_{sw} = 3$ MHz, $I_{L,p-p} = 5$ A



Frequency Domain – Test Cases (II)

- Test cases:
  1) $f_{sw} = 1$ MHz, $I_{L,p-p} = 5$ A,
  2) $f_{sw} = 3$ MHz, $I_{L,p-p} = 5$ A.
- **Absolute difference [dB] in magnitudes** of the current spectrum between commercial current sensor and:
  - nominal 50-mΩ model (nom.),
  - extracted model (extr.).

harmonic	1)		2)	
	nom.	extr.	nom.	extr.
f_{SW}	1.83	0.15	2.53	0.76
2nd	2.53	0.79	9.25	1.25
3rd	5.57	1.46	13.01	1.37
4th	7.46	1.82	15.46	2.54
5th	9.14	2.14	17.27	2.97

Outline

1. Introduction
2. Measurement Procedure
3. Lumped-Element Model of the Current-Sense Resistor
4. Validation of the Model
5. Conclusion

Conclusion

- Shunt measurement method for low-impedance DUT
- Lumped-element model of current-sense resistor
  - frequency-independent elements,
  - valid up to 100 MHz,
  - impact of skin effect,
  - impact of variation of model parameters.
- Validation of the model
  - time domain – ringing and overshoot modelled,
  - frequency domain – advantage at higher freqs.
- Accurate extraction of the sensed current for large-current high-freqency applications

Thank you for your attention!

Josip Bačmaga, M.Sc.
University of Zagreb, Croatia
Faculty of Electrical Engineering
and Computing
e-mail: josip.bacmaga@fer.hr